U.S. DEPARTMENT OF COMMERCE
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PB-252 565

MAGNITUDE OF SO2, NO, CO2, AND O2 STRATIFICATION IN POWER PLANT DUCTS

EXXON RESEARCH AND ENGINEERING COMPANY

PREPARED FOR
ENVIRONMENTAL SCIENCES RESEARCH LABORATORY

SEPTEMBER 1975

138201

PB 252 565

EPA-600/2-75-053
September 1975

Environmental Protection Technology Series

MAGNITUDE OF SO_2, NO, CO_2, AND O_2 STRATIFICATION IN POWER PLANT DUCTS

Environmental Sciences Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

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TECHNICAL REPORT DATA

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1. REPORT NO. EPA-600/2-75-053	2.	3. RECIPIENT'S ACCESSION NO. PB-252 565
4. TITLE AND SUBTITLE MAGNITUDE OF SO_2, NO, CO_2, AND O_2 STRATIFICATION IN POWER PLANT DUCTS		5. REPORT DATE September 1975 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) A. R. Crawford, M. W. Gregory, E. H. Manny, and W. Bartok		8. PERFORMING ORGANIZATION REPORT NO. EXXON/GRV.IDJAL.75
9. PERFORMING ORGANIZATION NAME AND ADDRESS Exxon Research and Engineering Company Government Research Laboratory P. O. Box 8 Linden, New Jersey 07036		10. PROGRAM ELEMENT NO. 1AA010 11. CONTRACT/GRANT NO. 68-02-1722
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Research Triangle Park, N.C. 27711		13. TYPE OF REPORT AND PERIOD COVERED final 14. SPONSORING AGENCY CODE EPA-ORD

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A field measurement study was conducted on utility boilers to determine combustion gas stratification in the ducting. One of the purposes of the study was to determine the optimum location for extracting representative gas samples for continuous monitoring. The results indicate that average gas concentration, velocity, and temperature, which were measured by traversing the inner 50% of the duct cross section, do not differ significantly from those obtained by traversing the entire duct. Also, sampling from only a limited number of points within the inner 50% of the duct usually yields a representative sample.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution	*Electric-power plants		13A
Measurement	Coal		14B
Field Tests	Oil		7D
Continuous Sampling	Boilers		21D
*Gas Sampling			10B
*Stratification			13A
Chemical ANalysis			

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 169
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/2-75-053
September 1975

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SUMMARY

Exxon Research and Engineering Company has conducted a field measurement program on utility boilers under EPA sponsorship to determine the optimum location in the boiler ducting for extracting representative gas samples for continuous monitoring. Under this contract, Exxon's mobile sampling/analytical system equipped with continuous monitors has been used to make measurements on seven fossil fuel-fired power boilers (six coal-, one coal/oil mixed fuel-fired) ranging in size from 125 to 800 MW. These boilers, including wall and tangentially fired units, had been recommended by the utility boiler manufacturers as being representative of their current design practices. Concentration profiles for two pollutants, SO_2 and NO, and for two stable combustion products, CO_2 and O_2, as well as velocity and temperature profiles were measured to establish the degree of point-to-point and duct-to-duct stratification of gaseous species.

The selection of sampling locations and the number of sampling points were aimed at obtaining representative gas samples. In all tests, sampling was done downstream of the air preheater (all units tested were equipped with rotary air preheaters) with one set of measurements performed 8 diameters up in the stack of an 800 MW power boiler. The number of sampling points at each location was determined by following EPA Method 1 guidelines as specified in the Federal Register.

The results indicate that stratification does exist in the flue gas ducting of power plant boilers and that single point sampling is inappropriate for obtaining representative gas samples. However, an analysis of the data shows that certain sampling techniques can be used to reduce the significance of gas stratification in obtaining representative samples.

It has been shown that gas component concentration averages, gas velocity averages, and gas temperature averages obtained by traversing the inner 50% of the duct cross section do not differ significantly from those obtained by traversing the entire duct. Furthermore, it has been found that sampling from only a limited number of points within the inner 50% usually yields a representative sample. Therefore, it is recommended that multi-point sampling probes be used. At least two probes of this type should be used per duct and they should be constructed so that samples are taken from zones of "equal areas" within the inner 50% of the duct. Results of the in-stack tests, as opposed to the in-duct tests, indicate that stack conditions are extremely uniform and that this should be the preferred extractive sampling location for gaseous species monitoring, provided that practical accessibility to such a sampling location is available.

1. INTRODUCTION

The objectives of continuous monitoring of air pollutant emissions from fossil fuel-fired power plant boilers are two-fold. First, reliable monitoring records should establish whether the unit under consideration has been in compliance with regulations. Second, continuous monitoring with direct reading output can signal the occurrence of upset process conditions that may result in excessive levels of air pollutant emissions. Such real-time warning is needed to enable the power plant operator to take immediate corrective action.

Since the advent of EPA emission regulations issued as required by the Air Quality Amendments of 1970 for stationary sources, there has been an increased emphasis placed on developing monitoring instrumentation for air pollutants. EPA established performance standards for new steam generators exceeding in size 250 million Btu/hr firing rate, and recommended emission standards to the States for units in the same size category to help prepare state implementation plans. In general, fossil fuel-fired power plants raise steam in boilers larger than the above limit, and are therefore subject to emission regulations. Thus, the emission levels of gaseous air pollutant species, SO_2 and NO_x, must be controlled for power plant installations.

Continuous monitoring of the effluent is much more efficient, productive, and less time-consuming than laborious grab sampling and wet chemical analytical methods. The availability of increasingly sophisticated and reliable monitoring instrumentation is a result of such considerations. In addition to air pollutants, there is a need for monitoring the concentrations of key gaseous components of combustion flue gases, specifically O_2 and CO_2. The O_2 concentration in the flue gas is the measure of the level of excess air used for combustion (provided the flue gas is not diluted by air leaks), an important parameter that affects boiler operability features such as flame stability, corrosion, slagging and thermal efficiency. The CO_2-O_2 relationship is a measure of the boiler performance for a given fuel, and reliable sampling and analytical measurements should agree with the calculated relationship based on fuel analysis for well adjusted boiler systems.

All monitoring instrumentation must be supplied with representative gas samples to make the results acceptable (except for in-stack, averaging monitors which also must be validated against primary standard methods based on direct sample extraction). Usually, stratification of gaseous species in power plant boiler ducts and stacks has been assumed to be of minor importance, because of the mixing and turbulence of the high velocity flue gas streams. This has been assumed to be the case, even though it is well known that the composition of the combustion gases produced in boiler furnaces is not uniform due to imbalances in air and fuel supplies to individual burners or groups of burners. The flow patterns prevailing in power plant furnaces fired with fossil fuels (particularly with coal or oil fuels) can further enhance the stratification of gas compositions. In most power plant boilers, the flue gas stream exiting from the furnace flows into two or more separate ducts. Thus, duct-to-duct stratification may complicate the problem of monitoring, in addition to stratification in individual ducts.

The ultimate goal of this measurement program was to determine the optimum location in the ducting for extracting representative sample streams to be supplied to gas monitors. This goal was achieved by measuring the SO_2, NO, CO_2 and O_2 concentration profiles in the flue gas ducting of seven representative fossil fuel-fired utility boilers to determine the magnitude of gaseous stratification. The lower the degree of stratification, the easier it will be to obtain representative gas samples by probing from a minimum number of duct positions. Following is a list of the units tested in this program:

1. Widows Creek Unit 5 (TVA)
2. Widows Creek Unit 7 (TVA)
3. E.C. Gaston Unit 5 (Southern Electric Generating Company)
4. Barry Unit 4 (Alabama Power Company)
5. Barry Unit 5 (Alabama Power Company)
6. Morgantown Unit 1 (Potomac Electric Power Company)
7. Navajo Unit 1 (Salt River Project)

In addition to gas concentration measurements, it was necessary to establish the temperature and velocity profiles of the gases being sampled. These data are needed for measuring flue gas flow rates and temperatures which are needed for calculating mass emission rates of pollutants, by combining flow rate, temperature and concentration measurements. The Exxon mobile sampling/analytical system was used to obtain the required emissions data.

2. CONCLUSIONS

This section of the report presents the conclusions and recommendations based on the results obtained in a field program conducted on seven representative fossil fuel-fired utility boilers. Tables 1-6 summarize the results of our stratification tests. As shown, with the exception of Widows Creek Unit 5, all the units were tangentially fired boilers. Also, all units were coal fired except for Morgantown Unit 1, which was a mixed fuel unit. Testing was performed with this boiler firing 75% oil and 25% coal. The units were tested under normal operating conditions, with the percent of full load ranging from a low of 63% during the Barry Unit 5 test to 100% on the Morgantown Unit 1 and Navajo Unit 1 tests.

The objective of this study having been the determination of the extent of the stratification of the gaseous components in boiler flue gas ducting downstream of the air preheaters, our testing was guided by the following criteria:

1. The determination of the magnitude of the point-to-point stratification at a given duct cross section.
2. The determination of the magnitude of the duct-to-duct stratification.

The magnitude of the point-to-point stratification is used to help determine the position within the duct cross section where the most representative gas sample can be withdrawn. In trying to determine this position, we first calculated the various total duct average gaseous component concentrations, the total duct average velocity, and the total duct average temperature. This was done by using the data obtained from all the sampling points. In an attempt to determine if a partial traverse of the duet cross section was sufficient to accurately measure gas component concentrations, the various "inner duct average" gaseous component concentrations, velocity, and temperature were calculated. These inner duct averages were determined by calculating the various averages neglecting the data taken at the outermost sampling points. These values are shown in Tables 1-6. It should be noted that all gaseous component concentrations have been corrected to a 3% O_2 basis to correct for dilution effects. In all the tests performed, excluding the outermost sampling points means that only the sampling points within the inner ∿50% (by area) of the duct cross section were used in calculating the averages. Results from the tests performed show that the total duct averages and the inner duct averages do not differ substantially. In only one case is the difference greater than 10%. This occurred at the Gaston Steam Plant where the inner duct O_2 average was 10.7% lower than the total duct O_2 average. This difference was attributed to air leaks. This indicates that sampling confined to traversing the inner 50% of the duct will allow a determination of the flue gas composition which is very close to the actual composition. It will be shown later that single point sampling is inadequate in most instances and it will be necessary to take a composite sample from three or more points within the inner 50% of the duct cross section to obtain a representative sample.

TABLE 1

STRATIFICATION RESULTS FOR SO_2 (ppm) CORRECTED TO A 3% O_2 BASIS

Unit	Type of Firing	Full Load Rating, MW	Load When Tested, MW	% Full Load	Duct A					Duct B					Boiler		
					Total Duct Average ($\overline{X}_A$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Total Duct Average ($\overline{X}_B$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Average ($\overline{X}$)	% Difference Between $\overline{X}$ and $\overline{X}_A$	% Difference Between $\overline{X}$ and $\overline{X}_B$
Widows Creek No. 5	Front Wall	125	100	80	1417	118	1414	130	-0.2	1397	145	1398	152	+0.1	1407	+0.7	-0.7
Widows Creek No. 7	Tangential	575	400	70	2578	438	2545	331	-1.3	2426	325	2405	291	-0.9	2502	+3.0	-3.0
E.C. Gaston No. 5	Tangential	900	850	94	1162	183	1211	254	+4.2	1190	86	1203	93	+1.1	1176	-1.2	+1.2
Barry No. 4	Tangential	350	240	69	1746	51	1751	46	+0.3	1742	54	1746	43	+0.2	1744	+0.1	-0.1
Barry No. 5	Tangential	712	450	63	2409	84	2446	45	+1.5	2312	138	2334	80	+1.0	2361	+2.0	-2.0
Morgantown No. 1	Tangential	575	575	100	1353	53	1358	52	+0.4	1261	44	1262	40	+0.1	1307	+3.5	-3.5
Navajo No. 1 (Ducts A and B)	Tangential	800	800	100	438	35	433	21	-1.1	507	44	525	24	+3.6	461	-5.0	+10.0
Navajo No. 1 (Ducts C and D)	Tangential	800	800	100	435	40	446	25	+2.5	463	72	493	18	+6.5	461	-5.6	-0.4

TABLE 2

STRATIFICATION RESULTS FOR NO (ppm) CORRECTED TO A 3% O_2 BASIS

Unit	Type of Firing	Full Load Rating, MW	Load When Tested, MW	% Full Load	Duct A					Duct B					Boiler		
					Total Duct Average ($\bar{X}_A$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Total Duct Average ($\bar{X}_B$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Average ($\bar{X}$)	% Difference Between $\bar{X}$ and $\bar{X}_A$	% Difference Between $\bar{X}$ and $\bar{X}_B$
Widows Creek No. 5	Front Wall	125	100	80	564	19	563	21	-0.2	578	17	579	15	+0.2	571	-1.2	+1.2
Widows Creek No. 7	Tangential	575	400	70	341	23	340	23	-0.3	386	20	386	17	0.0	364	-6.2	+6.2
E.C. Gaston No. 5	Tangential	900	850	94	605	22	614	15	+1.5	514	12	516	11	+0.4	560	+8.1	-8.1
Barry No. 4	Tangential	350	240	69	359	23	354	26	-1.4	377	20	373	19	-1.1	368	-2.4	+2.4
Barry No. 5	Tangential	712	450	63	371	21	374	23	+0.8	343	14	346	8	+0.9	357	+3.9	-3.9
Morgantown No. 1	Tangential	575	575	100	374	31	369	33	-1.3	419	35	420	28	+0.2	397	-5.8	+5.8
Navajo No. 1 (Ducts A and B)	Tangential	800	800	100	310	11	313	8	+1.0	310	9	308	8	-0.6	322	-3.7	-3.7
Navajo No. 1 (Ducts C and D)	Tangential	800	800	100	333	8	331	7	-0.6	335	10	331	6	-1.2	322	+3.4	+4.0

TABLE 3

STRATIFICATION RESULTS FOR CO_2 (%) CORRECTED TO A 3% O_2 BASIS

					Duct A					Duct B					Boiler		
Unit	Type of Firing	Full Load Rating, MW	Load When Tested, MW	% Full Load	Total Duct Average ($\overline{X}_A$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Total Duct Average ($\overline{X}_B$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Average ($\overline{X}$)	% Difference Between $\overline{X}$ and $\overline{X}_A$	% Difference Between $\overline{X}$ and $\overline{X}_B$
Widows Creek No. 5	Front Wall	125	100	80	16.0	0.4	16.0	0.3	0.0	15.9	0.6	15.9	0.76	0.0	15.95	+0.3	-0.3
Widows Creek No. 7	Tangential	575	400	70	14.4	0.8	14.4	0.9	0.0	14.5	0.7	14.8	0.94	+2.1	14.45	-0.4	+0.4
E.C. Gaston No. 5	Tangential	900	850	94	14.4	0.6	14.6	0.6	+1.4	14.7	0.5	14.8	0.28	+0.7	14.55	-1.0	+1.0
Barry No. 4	Tangential	350	240	69	15.9	0.5	16.0	0.6	+0.3	15.9	0.5	15.8	0.54	-0.1	15.91	+0.4	-0.4
Barry No. 5	Tangential	712	450	63	15.3	0.5	15.	0.4	+0.9	14.3	0.9	14.5	0.71	+1.8	14.76	+3.4	-3.4
Morgantown No. 1	Tangential	575	575	100	14.2	0.5	14.3	0.4	+0.7	14.1	0.4	14.1	0.35	0.0	14.15	+0.4	-0.4
Navajo No. 1 (Ducts A and B)	Tangential	800	800	100	15.7	0.2	15.7	0.1	0.0	15.5	0.2	15.5	0.1	0.0	15.5	+1.3	0.0
Navajo No. 1 (Ducts C and D)	Tangential	800	800	100	15.5	0.3	15.6	0.1	+0.6	15.3	0.2	15.2	0.2	-0.7	15.5	0.0	-1.3

TABLE 4

STRATIFICATION RESULTS FOR O_2 (%)

Unit	Type of Firing	Full Load Rating, MW	Load When Tested, MW	% Full Load	Duct A					Duct B					Boiler		
					Total Duct Average ($\overline{X}_A$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Total Duct Average ($\overline{X}_B$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Average ($\overline{X}$)	% Difference Between $\overline{X}$ and $\overline{X}_A$	% Difference Between $\overline{X}$ and $\overline{X}_B$
Widows Creek No. 5	Front Wall	125	100	80	7.7	0.9	7.6	0.7	-1.3	8.7	0.8	8.7	0.6	0.0	8.20	-6.1	+6.1
Widows Creek No. 7	Tangential	575	400	70	4.3	0.8	4.0	0.5	-7.0	4.8	0.6	4.4	0.3	-8.3	4.55	-5.5	+5.5
E.C. Gaston No. 5	Tangential	900	850	94	6.1	0.7	5.6	0.2	-8.2	5.6	0.8	5.0	0.3	-10.7	5.85	+4.3	-4.3
Barry No. 4	Tangential	350	240	69	5.8	0.6	5.7	0.7	-1.7	6.1	0.6	5.9	0.5	-3.3	5.95	-2.5	+2.5
Barry No. 5	Tangential	712	450	63	5.0	0.6	4.6	0.9	-8.0	7.8	1.2	7.4	0.8	-5.1	6.40	-22.9*	+22.9
Morgantown No. 1	Tangential	575	575	100	5.2	1.1	4.7	0.4	-9.6	5.4	0.9	5.1	0.7	-5.6	5.15	+1.0	-1.0
Navajo No. 1 (Ducts A and B)	Tangential	800	800	100	5.7	0.2	5.6	0.1	-1.8	6.9	0.1	6.8	0.1	-1.4	6.5	-12.3	+6.2
Navajo No. 1 (Ducts C and D)	Tangential	800	800	100	6.5	0.2	6.4	0.1	-1.5	6.9	0.2	6.9	0.1	0.0	6.5	0.0	+6.2

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* On a % excess air basis this difference would be much smaller (i.e., $\overline{X}$ = 143% vs. $\overline{X}_A$ = 130%, $\overline{X}_B$ = 158%).

TABLE 5

STRATIFICATION RESULTS FOR VELOCITY (M/S)

Unit	Type of Firing	Full Load Rating, MW	Load When Tested, MW	% Full Load	Duct A					Duct B					Boiler		
					Total Duct Average ($\overline{X}_A$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Total Duct Average ($\overline{X}_B$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Average ($\overline{X}$)	% Difference Between $\overline{X}$ and $\overline{X}_A$	% Difference Between $\overline{X}$ and $\overline{X}_B$
Widows Creek No. 5	Front Wall	125	100	80	9.6	2.0	9.1	2.0	-5.2	9.0	2.6	8.0	2.9	-6.7	9.30	+3.2	-3.2
Widows Creek No. 7	Tangential	575	400	70	6.4	2.3	6.4	1.7	0.0	6.3	1.8	6.4	1.6	+1.6	6.35	+0.8	-0.8
E.C. Gaston No. 5	Tangential	900	850	94	17.1	6.5	17.9	4.0	+4.7	13.2	4.8	14.0	2.8	+6.1	15.15	+12.9	-12.9
Barry No. 4	Tangential	350	240	69	12.0	1.5	11.1	1.0	-7.4	11.5	1.5	10.7	0.7	-7.5	11.75	+2.3	-2.3
Barry No. 5	Tangential	712	450	63	5.3	1.0	5.6	0.8	+5.1	4.7	0.9	5.0	0.8	+6.0	5.01	+6.6	-6.6
Morgantown No. 1	Tangential	575	575	100	13.8	4.5	13.6	3.7	-1.4	14.7	4.9	14.5	4.0	-1.4	14.2	-2.8	+2.8
Navajo No. 1 (Ducts A and B)	Tangential	800	800	100	10.2	1.3	10.1	0.9	-1.0	9.5	1.4	9.1	0.9	-4.2	9.5	+7.4	0.0
Navajo No. 1 (Ducts C and D)	Tangential	800	800	100	9.4	1.1	9.2	0.8	-2.1	8.9	1.9	8.4	1.5	-5.6	9.5	-1.1	-6.3

TABLE 6

STRATIFICATION RESULTS FOR TEMPERATURE (°C)

Unit	Type of Firing	Full Load Rating, MW	Load When Tested, MW	% Full Load	Duct A					Duct B					Boiler		
					Total Duct Average ($\bar{X}_A$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Total Duct Average ($\bar{X}_B$)	Total Duct Standard Deviation	Inner Duct Average	Inner Duct Standard Deviation	% Difference Between Averages	Average ($\bar{X}$)	% Difference Between $\bar{X}$ and $\bar{X}_A$	% Difference Between $\bar{X}$ and $\bar{X}_B$
Widows Creek No. 5	Front Wall	125	100	80	183	3	183	3	0.0	172	4	171	3	-0.6	177.5	+3.1	-3.1
Widows Creek No. 7	Tangential	575	400	70	141	10	143	7	+1.4	134	13	139	9	+3.7	137.5	+2.6	-2.6
E.C. Gaston No. 5	Tangential	900	850	94	141	13	144	7	+1.4	121	12	125	8	+3.3	131.5	+8.0	-8.0
Barry No. 4	Tangential	350	240	69	159	19	160	8	+0.6	131	7	130	6	-0.8	144.5	+9.7	-9.7
Barry No. 5	Tangential	712	450	63	119	8	121	6	+1.7	117	11	120	10	+2.6	118.0	+0.9	-0.9
Morgantown No. 1	Tangential	575	575	100	143	11	143	8	0.0	138	9	137	8	-0.7	140.5	+2.1	-2.1
Navajo No. 1 (Ducts A and B)	Tangential	800	800	100	145	12	146	12	+0.7	129	8	132	1	+2.3	140	+3.6	-7.9
Navajo No. 1 (Ducts C and D)	Tangential	800	800	100	130	10	133	5	+2.3	154	4	156	2	+1.3	140	-7.1	10.0

In determining the magnitude of the duct-to-duct stratification, first the boiler averages were calculated for the various gaseous components, the velocity, and the temperature. These averages were then compared with the averages for the two individual ducts from which sampling was done. Data obtained from the tests indicate that there is negligible duct-to-duct stratification. However, the most representative measurements would be obtained by taking a composite sample from both ducts.

As shown in the previous analysis, our test results indicate that gas component concentration averages, gas velocity averages, and gas temperature averages obtained by traversing the inner 50% of the duct cross section do not differ significantly from those obtained by traversing the entire duct cross section. This indicates that when measuring emission levels a substantial reduction in time can be obtained without any significant loss in accuracy if only the inner portion of the duct is traversed. However, even traversing only the inner portion of the duct requires a significant expenditure of time and energy. The ideal situation would exist if sampling would only have to be done from a single point within the duct.

Therefore, to determine if a single sampling location where a representative sampling could be extracted existed, the following analysis was made. Consider the two sample statistics, the average ($\overline{X}$) and the standard deviation (σ). These functions contain some useful information even if nothing is known about the form of the observed distribution. They contain even more information if certain conditions are satisfied. Tchebycheff's inequality enables us to state, with no reservations whatsoever, that more than $(1-1/t^2)$ of the total number of observations (n) lie within the limits $\overline{X} + t\sigma$ (where $t > 1$) (4). The Camp-Meidell inequality states that under certain conditions more than $(1-1/2.25\ t^2)$ of the total number of observations lie within the limits $\overline{X} + t\sigma$. The conditions to be satisfied are:

(1) The observed distribution has one peak.

(2) The mode is equal to the mean.

(3) The distribution function falls off continuously on either side of the mode.

If the observations are taken from a controlled process, the Normal Probability Distribution may be used to give the percentage of observations within certain limits. Among other things, the concept of control includes the idea of homogeneous data--a set of observations resulting from measurements made under essentially the same conditions. It is sufficient to note that if data are obtained under controlled conditions, the form of curve which will best represent the observed frequency distribution may, for most practical purposes, be assumed to be that defined by the Normal Law. The three distributions discussed above are compared in Table 7.

TABLE 7

COMPARISON OF ESTIMATED PERCENTAGES OF THE TOTAL OBSERVATIONS LYING WITHIN GIVEN RANGES

Limits	Normal Law	Camp-Meidell's Inequality	Tchebycheff's Inequality
$\overline{X} \pm 1\sigma$	68.3	55.5	--
$\overline{X} \pm 2\sigma$	95.4	88.9	75.0
$\overline{X} \pm 3\sigma$	99.7	95.1	88.9
$\overline{X} \pm 4\sigma$	99.994	97.2	93.7
$\overline{X} \pm 5\sigma$	99.9999	98.2	96.2

For the SO_2, NO, CO_2, and O_2 concentrations, gas velocity, and gas temperature, the following quantities were calculated: $\bar{X} - \sigma$, $\bar{X} + \sigma$, $\bar{X} - 2\sigma$, and $\bar{X} + 2\sigma$ ($\bar{X}$ represents the inner duct average reduced to a 3% O_2 basis and σ represents the inner duct standard deviation). If a Normal Probability Distribution is assumed, then for samples taken from the inner 50% of the duct cross section, we can estimate that more than 95% of these observations will lie within $\bar{X} + 2\sigma$ and more than 68% lie within $\bar{X} \pm 1\sigma$. The percent difference between the $\pm 1\sigma$ and $\pm 2\sigma$ range limits and the total duct average obtained by traversing the entire duct were also calculated to determine if a single measurement would reasonably represent the duct average. The results of the calculations are shown in Tables 8-13. The results can be summarized as follows:

1. $\underline{SO_2}$ Measurements

For most units tested $\bar{X}_{SO_2} \pm 2\sigma$ never differed from the total duct SO_2 average by more than $\pm 20\%$. Only the Widows Creek Unit 7 and E.C. Gaston Unit 5 (Duct A) test results show a significant difference ($\pm 27\%$ and $\pm 48\%$, respectively).

2. NO Measurements

For all units tested $\bar{X}_{NO} \pm 2\sigma$ never differed from the total duct NO average by more than $\pm 19\%$.

3. CO_2 Measurements

For all units tested $\bar{X}_{CO_2} \pm 2\sigma$ never differed from the total duct CO_2 average by more than $\pm 15\%$. Also, the measured CO_2 concentrations correlate well with the O_2 concentrations, exhibiting an inverse relationship.

4. O_2 Measurements

In general, the difference between $\bar{X}_{O_2} \pm 2\sigma$ and the total duct O_2 average was significant for the units tested. Our data shows that the Barry Unit 5 results exhibit the greatest deviation ($\pm 44\%$ on Duct A). These significant differences can probably be attributed to air leaks.

5. Velocity Measurements

For all units tested $\bar{X}_{Vel.} \pm 2\sigma$ differed significantly from the total duct velocity average. As expected, our results indicate that there is very little variation in our in-stack velocity measurements.

6. Temperature Measurements

For all units tested $\bar{X}_{Temp.} \pm 2\sigma$ never differed from the total duct temperature average by more than 20%. Also, since most flue gas calculations are done on an absolute temperature scale, the absolute temperature stratification will be less than shown.

TABLE 8

STRATIFICATION RESULTS - SO_2 (ppm) CORRECTED TO A 3% O_2 BASIS

Unit (Duct A)	Total Duct Average ($\overline{X}_A$)	Inner Duct Average ($\overline{X}_a$)	Inner Duct Standard Deviation (σ)	$\overline{X}_a - \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - \sigma$)	$\overline{X}_a + \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + \sigma$)	$\overline{X}_a - 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - 2\sigma$)	$\overline{X}_a + 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + 2\sigma$)
Widows Creek No. 5	1417	1414	130	1284	-9.4	1544	9.0	1154	-18.6	1674	18.1
Widows Creek No. 7	2578	2545	331	2214	-14.1	2876	11.6	1883	-27.0	3207	24.4
Gaston No. 5	1162	1211	254	957	-17.6	1465	26.1	703	-39.5	1719	47.9
Barry No. 4	1746	1751	46	1705	-2.3	1797	2.9	1659	-5.0	1843	5.6
Barry No. 5	2409	2446	45	2401	-0.3	2491	3.4	2356	-2.2	2536	5.3
Morgantown No. 1	1353	1358	52	1306	-3.5	1410	4.2	1254	-7.3	1462	8.1
Navajo No. 1	438	433	21	412	-5.9	454	3.7	391	-10.7	475	8.4

TABLE 8 (Cont'd.)

STRATIFICATION RESULTS - SO_2 (ppm) CORRECTED TO A 3% O_2 BASIS

Unit (Duct B)	Total Duct Average ($\overline{X}_B$)	Inner Duct Average ($\overline{X}_b$)	Inner Duct Standard Deviation (σ)	$\overline{X}_b - \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - \sigma$)	$\overline{X}_b + \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + \sigma$)	$\overline{X}_b - 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - 2\sigma$)	$\overline{X}_b + 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + 2\sigma$)
Widows Creek No. 5	1397	1398	152	1246	-10.8	1550	11.0	1094	-21.7	1702	21.8
Widows Creek No. 7	2426	2405	291	2114	-12.9	2696	11.1	1823	-24.9	2987	23.1
Gaston No. 5	1190	1203	93	1100	-7.6	1296	8.9	1007	-15.4	1389	16.7
Barry No. 4	1742	1746	43	1703	-2.2	1789	2.7	1660	-4.7	1832	5.2
Barry No. 5	2312	2334	80	2254	-2.5	2414	4.4	2174	-6.0	2494	7.9
Morgantown No. 1	1261	1262	40	1222	-3.1	1302	3.3	1182	-6.3	1342	6.4
Navajo No. 1	507	525	24	501	-1.2	549	8.3	477	-5.9	573	13.0

TABLE 8 (Cont'd.)

STRATIFICATION RESULTS - SO_2 (ppm) CORRECTED TO A 3% O_2 BASIS

Unit (Duct C)	Total Duct Average ($\overline{X}_C$)	Inner Duct Average ($\overline{X}_c$)	Inner Duct Standard Deviation (σ)	$\overline{X}_c - \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - \sigma$)	$\overline{X}_c + \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + \sigma$)	$\overline{X}_c - 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - 2\sigma$)	$\overline{X}_c + 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + 2\sigma$)
Navajo No. 1	435	446	25	421	-3.2	471	8.3	396	-9.0	496	14.0

Unit (Duct D)	Total Duct Average ($\overline{X}_D$)	Inner Duct Average ($\overline{X}_d$)	Inner Duct Standard Deviation (σ)	$\overline{X}_d - \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - \sigma$)	$\overline{X}_d + \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + \sigma$)	$\overline{X}_d - 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - 2\sigma$)	$\overline{X}_d + 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + 2\sigma$)
Navajo No. 1	463	493	18	475	2.6	511	10.4	457	-1.3	529	14.3

TABLE 9

STRATIFICATION RESULTS - NO (ppm) CORRECTED TO A 3% O_2 BASIS

Unit (Duct A)	Total Duct Average ($\overline{X}_A$)	Inner Duct Average ($\overline{X}_a$)	Inner Duct Standard Deviation (σ)	$\overline{X}_a - \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - \sigma$)	$\overline{X}_a + \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + \sigma$)	$\overline{X}_a - 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - 2\sigma$)	$\overline{X}_a + 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + 2\sigma$)
Widows Creek No. 5	564	563	21	542	-3.9	584	3.7	521	-7.6	605	7.3
Widows Creek No. 7	341	340	23	317	-7.0	363	6.5	294	-13.8	386	13.2
Gaston No. 5	605	614	15	599	-1.0	629	4.0	584	-3.5	644	6.4
Barry No. 4	359	354	26	328	-8.6	380	5.8	302	-16.9	406	13.1
Barry No. 5	371	374	23	351	-5.4	397	7.0	328	-11.6	420	13.2
Morgantown No. 1	374	369	33	336	-10.2	402	7.5	303	-19.0	435	16.3
Navajo No. 1	310	313	8	305	-1.6	321	3.5	297	-4.2	329	6.1

TABLE 9 (Cont'd.)

STRATIFICATION RESULTS - NO (ppm) CORRECTED TO A 3% O_2 BASIS

Unit (Duct B)	Total Duct Average ($\overline{X}_B$)	Inner Duct Average ($\overline{X}_b$)	Inner Duct Standard Deviation (σ)	$\overline{X}_b - \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - \sigma$)	$\overline{X}_b + \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + \sigma$)	$\overline{X}_b - 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - 2\sigma$)	$\overline{X}_b + 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + 2\sigma$)
Widows Creek No. 5	578	579	16	563	-2.6	595	2.9	547	-5.4	611	5.7
Widows Creek No. 7	386	386	17	369	-4.4	403	4.4	352	-8.8	420	8.8
Gaston No. 5	514	516	11	505	-1.8	527	2.5	494	-3.9	538	4.7
Barry No. 4	377	373	19	354	-6.1	392	4.0	335	-11.1	411	9.0
Barry No. 5	343	346	8	338	-1.5	354	3.2	330	-3.8	362	5.5
Morgantown No. 1	419	420	28	392	-6.4	448	6.9	364	-13.1	476	13.6
Navajo No. 1	310	308	8	300	-3.2	316	1.9	292	-5.8	324	4.5

TABLE 9 (Cont'd.)

STRATIFICATION RESULTS - NO (ppm) CORRECTED TO A 3% O_2 BASIS

Unit (Duct C)	Total Duct Average ($\overline{X}_C$)	Inner Duct Average ($\overline{X}_c$)	Inner Duct Standard Deviation (σ)	$\overline{X}_c - \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - \sigma$)	$\overline{X}_c + \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + \sigma$)	$\overline{X}_c - 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - 2\sigma$)	$\overline{X}_c + 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + 2\sigma$)
Navajo No. 1	333	331	7	324	-2.7	338	1.5	317	-4.8	345	3.6

Unit (Duct D)	Total Duct Average ($\overline{X}_D$)	Inner Duct Average ($\overline{X}_d$)	Inner Duct Standard Deviation (σ)	$\overline{X}_d - \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - \sigma$)	$\overline{X}_d + \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + \sigma$)	$\overline{X}_d - 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - 2\sigma$)	$\overline{X}_d + 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + 2\sigma$)
Navajo No. 1	335	331	6	325	-3.0	337	0.6	319	-4.8	343	2.4

TABLE 10

STRATIFICATION RESULTS - CO_2 (%) CORRECTED TO A 3% O_2 BASIS

Unit (Duct A)	Total Duct Average ($\overline{X}_A$)	Inner Duct Average ($\overline{X}_a$)	Inner Duct Standard Deviation (σ)	$\overline{X}_a - \sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a - \sigma)$	$\overline{X}_a + \sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a + \sigma)$	$\overline{X}_a - 2\sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a - 2\sigma)$	$\overline{X}_a + 2\sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a + 2\sigma)$
Widows Creek No. 5	16.0	16.0	0.3	15.7	-1.9	16.3	1.9	15.4	-3.8	16.6	3.8
Widows Creek No. 7	14.4	14.4	0.9	13.5	-6.3	15.3	6.3	12.6	-12.5	16.2	12.5
Gaston No. 5	14.4	14.6	0.6	14.0	-2.8	15.2	5.6	13.4	-6.9	15.8	9.7
Barry No. 4	16.0	16.0	0.6	15.4	-3.8	16.6	3.8	14.8	-7.5	17.2	7.5
Barry No. 5	15.3	15.4	0.4	15.0	-2.0	15.8	3.3	14.6	-4.6	16.2	5.9
Morgantown No. 1	14.2	14.3	0.4	13.9	-2.1	14.7	3.5	13.5	-4.9	15.1	6.3
Navajo No. 1	15.7	15.7	0.1	15.6	-0.6	15.8	0.6	15.5	-1.3	15.9	1.3

TABLE 10 (Cont'd.)

STRATIFICATION RESULTS - CO_2 (%) CORRECTED TO A 3% O_2 BASIS

Unit (Duct B)	Total Duct Average ($\overline{X}_B$)	Inner Duct Average ($\overline{X}_b$)	Inner Duct Standard Deviation (σ)	$\overline{X}_b - \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - \sigma$)	$\overline{X}_b + \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + \sigma$)	$\overline{X}_b - 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - 2\sigma$)	$\overline{X}_b + 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + 2\sigma$)
Widows Creek No. 5	15.9	15.9	0.8	15.1	-5.0	16.7	5.0	14.3	-10.1	17.5	10.1
Widows Creek No. 7	14.5	14.8	0.9	13.9	-4.1	15.7	8.3	13.0	-10.3	16.6	14.5
Gaston No. 5	14.7	14.8	0.3	14.5	-1.4	15.1	2.7	14.2	-3.4	15.4	4.8
Barry No. 4	15.9	15.8	0.5	15.3	-3.8	16.3	2.5	14.8	-6.9	16.8	5.7
Barry No. 5	14.3	14.5	0.7	13.8	-3.5	15.2	6.3	13.1	-8.4	15.9	11.2
Morgantown No. 1	14.1	14.1	0.4	13.7	-2.8	14.5	2.8	13.3	-5.7	14.9	5.7
Navajo No. 1	15.5	15.5	0.1	15.4	-0.6	15.6	0.6	15.3	-1.3	15.7	1.3

TABLE 10 (Cont'd.)

STRATIFICATION RESULTS - CO_2 (%) CORRECTED TO A 3% O_2 BASIS

Unit (Duct C)	Total Duct Average ($\overline{X}_C$)	Inner Duct Average ($\overline{X}_c$)	Inner Duct Standard Deviation (σ)	$\overline{X}_c - \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - \sigma$)	$\overline{X}_c + \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + \sigma$)	$\overline{X}_c - 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - 2\sigma$)	$\overline{X}_c + 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + 2\sigma$)
Navajo No. 1	15.5	15.6	0.1	15.5	0.0	15.7	1.3	15.4	-0.6	15.8	1.9

Unit (Duct D)	Total Duct Average ($\overline{X}_D$)	Inner Duct Average ($\overline{X}_d$)	Inner Duct Standard Deviation (σ)	$\overline{X}_d - \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - \sigma$)	$\overline{X}_d + \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + \sigma$)	$\overline{X}_d - 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - 2\sigma$)	$\overline{X}_d + 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + 2\sigma$)
Navajo No. 1	15.3	15.2	0.2	15.0	-2.0	15.4	0.7	14.8	-3.3	15.6	2.0

TABLE 11

STRATIFICATION RESULTS - O_2 (%)

Unit (Duct A)	Total Duct Average ($\overline{X}_A$)	Inner Duct Average ($\overline{X}_a$)	Inner Duct Standard Deviation (σ)	$\overline{X}_a - \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - \sigma$)	$\overline{X}_a + \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + \sigma$)	$\overline{X}_a - 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - 2\sigma$)	$\overline{X}_a + 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + 2\sigma$)
Widows Creek No. 5	7.7	7.6	0.7	6.9	-10.4	8.3	7.8	6.2	-19.5	9.0	16.9
Widows Creek No. 7	4.3	4.0	0.5	3.5	-18.6	4.5	4.7	3.0	-30.2	5.0	16.3
Gaston No. 5	6.1	5.6	0.2	5.4	-11.5	5.8	-4.9	5.2	-14.8	6.0	-1.6
Barry No. 4	5.8	5.7	0.7	5.0	-13.8	6.4	10.3	4.3	-25.9	7.1	22.4
Barry No. 5	5.0	4.6	0.9	3.7	-26.0	5.5	10.0	2.8	-44.0	6.4	28.0
Morgantown No. 1	5.2	4.7	0.4	4.3	-17.3	5.1	-1.9	3.9	-25.0	5.5	5.8
Navajo No. 1	5.7	5.6	0.1	5.5	-3.5	5.7	0.0	5.4	-5.3	5.8	1.8

TABLE 11 (Cont'd.)

STRATIFICATION RESULTS - O_2 (%)

Unit (Duct B)	Total Duct Average ($\overline{X}_B$)	Inner Duct Average ($\overline{X}_b$)	Inner Duct Standard Deviation (σ)	$\overline{X}_b - \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - \sigma$)	$\overline{X}_b + \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + \sigma$)	$\overline{X}_b - 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - 2\sigma$)	$\overline{X}_b + 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + 2\sigma$)
Widows Creek No. 5	8.7	8.7	0.6	8.1	-6.9	9.3	6.9	7.5	-13.8	9.9	13.8
Widows Creek No. 7	4.8	4.4	0.3	4.1	-14.6	4.7	-2.1	3.8	-20.8	5.0	4.2
Gaston No. 5	5.6	5.0	0.3	4.7	-16.1	5.3	-5.4	4.4	-21.4	5.6	0.0
Barry No. 4	6.1	5.9	0.5	5.4	-11.5	6.4	4.9	4.9	-19.7	6.9	13.1
Barry No. 5	7.8	7.4	0.8	6.6	-15.4	8.2	5.1	5.8	-25.6	9.0	15.4
Morgantown No. 1	5.4	5.1	0.7	4.4	-18.5	5.8	7.4	3.7	-31.5	6.5	20.4
Navajo No. 1	6.9	6.8	0.1	6.7	-2.9	6.9	0.0	6.6	-4.3	7.0	1.4

TABLE 11 (Cont'd.)

STRATIFICATION RESULTS - O_2 (%)

Unit (Duct C)	Total Duct Average ($\overline{X}_C$)	Inner Duct Average ($\overline{X}_c$)	Inner Duct Standard Deviation (σ)	$\overline{X}_c - \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - \sigma$)	$\overline{X}_c + \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + \sigma$)	$\overline{X}_c - 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - 2\sigma$)	$\overline{X}_c + 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + 2\sigma$)
Navajo No. 1	6.5	6.4	0.1	6.3	-3.1	6.5	0.0	6.2	-4.6	6.6	1.5

Unit (Duct D)	Total Duct Average ($\overline{X}_D$)	Inner Duct Average ($\overline{X}_d$)	Inner Duct Standard Deviation (σ)	$\overline{X}_d - \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - \sigma$)	$\overline{X}_d + \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + \sigma$)	$\overline{X}_d - 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - 2\sigma$)	$\overline{X}_d + 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + 2\sigma$)
Navajo No. 1	6.9	6.9	0.1	6.8	-1.4	7.0	1.4	6.7	-2.9	7.1	2.9

TABLE 12

STRATIFICATION RESULTS - VELOCITY (M/S)

Unit (Duct A)	Total Duct Average ($\overline{X}_A$)	Inner Duct Average ($\overline{X}_a$)	Inner Duct Standard Deviation (σ)	$\overline{X}_a - \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - \sigma$)	$\overline{X}_a + \sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + \sigma$)	$\overline{X}_a - 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a - 2\sigma$)	$\overline{X}_a + 2\sigma$	% Difference Between $\overline{X}_A$ and ($\overline{X}_a + 2\sigma$)
Widows Creek No. 5	9.6	9.1	2.0	7.1	-26.0	11.1	15.6	5.1	-46.9	13.1	36.5
Widows Creek No. 7	6.4	6.4	1.7	4.7	-26.6	8.1	26.6	3.0	-53.1	9.8	53.1
Gaston No. 5	17.1	17.9	4.0	13.9	-18.7	21.9	28.1	9.9	-42.1	25.9	51.5
Barry No. 4	12.0	11.1	1.0	10.1	-15.8	12.1	0.8	9.1	-24.2	13.1	9.2
Barry No. 5	5.3	5.6	0.8	4.8	-9.4	6.4	20.8	4.0	-24.5	7.2	35.8
Morgantown No. 1	13.8	13.6	3.7	9.9	-28.3	17.3	25.4	6.2	-28.3	21.0	52.2
Navajo No. 1	10.2	10.1	0.9	9.2	-9.8	11.0	7.8	8.3	-18.6	11.9	16.7

TABLE 12 (Cont'd.)

STRATIFICATION RESULTS - VELOCITY (M/S)

Unit (Duct B)	**Total Duct Average ($\overline{X}_B$)**	**Inner Duct Average ($\overline{X}_b$)**	Inner Duct Standard Deviation (σ)	$\overline{X}_b - \sigma$	**% Difference Between** $\overline{X}_B$ and ($\overline{X}_b - \sigma$)	$\overline{X}_b + \sigma$	**% Difference Between** $\overline{X}_B$ and ($\overline{X}_b + \sigma$)	$\overline{X}_b - 2\sigma$	**% Difference Between** $\overline{X}_B$ and ($\overline{X}_b - 2\sigma$)	$\overline{X}_b + 2\sigma$	**% Difference Between** $\overline{X}_B$ and ($\overline{X}_b + 2\sigma$)
Widows Creek No. 5	9.0	8.0	2.9	5.1	-43.3	10.9	21.1	2.2	-75.6	13.8	53.3
Widows Creek No. 7	6.3	6.4	1.6	4.8	-23.8	8.0	27.0	3.2	-49.2	9.6	52.4
Gaston No. 5	13.3	14.0	2.7	11.3	-15.0	16.7	25.7	8.6	-35.3	19.4	45.9
Barry No. 4	11.5	10.7	0.7	10.0	-13.0	11.4	-0.9	9.3	-19.1	12.1	5.2
Barry No. 5	4.7	5.0	0.8	4.2	-10.6	5.8	23.4	3.4	-27.7	6.6	40.4
Morgantown No. 1	14.7	14.5	4.0	10.5	-28.6	18.5	25.9	6.5	-55.8	22.5	53.1
Navajo No. 1	9.5	9.1	0.9	8.2	-13.7	10.0	5.3	7.3	-23.2	10.9	14.7

TABLE 12 (Cont'd.)

STRATIFICATION RESULTS - VELOCITY (M/S)

Unit (Duct C)	Total Duct Average $(\overline{X}_C)$	Inner Duct Average $(\overline{X}_c)$	Inner Duct Standard Deviation (σ)	$\overline{X}_c - \sigma$	% Difference Between $\overline{X}_C$ and $(\overline{X}_c - \sigma)$	$\overline{X}_c + \sigma$	% Difference Between $\overline{X}_C$ and $(\overline{X}_c + \sigma)$	$\overline{X}_c - 2\sigma$	% Difference Between $\overline{X}_C$ and $(\overline{X}_c - 2\sigma)$	$\overline{X}_c + 2\sigma$	% Difference Between $\overline{X}_C$ and $(\overline{X}_c + 2\sigma)$
Navajo No. 1	9.4	9.2	0.8	8.4	-10.6	10.0	6.4	7.6	-19.1	10.8	14.9

Unit (Duct D)	Total Duct Average $(\overline{X}_D)$	Inner Duct Average $(\overline{X}_d)$	Inner Duct Standard Deviation (σ)	$\overline{X}_d - \sigma$	% Difference Between $\overline{X}_D$ and $(\overline{X}_d - \sigma)$	$\overline{X}_d + \sigma$	% Difference Between $\overline{X}_D$ and $(\overline{X}_d + \sigma)$	$\overline{X}_d - 2\sigma$	% Difference Between $\overline{X}_D$ and $(\overline{X}_d - 2\sigma)$	$\overline{X}_d + 2\sigma$	% Difference Between $\overline{X}_D$ and $(\overline{X}_d + 2\sigma)$
Navajo No. 1	8.9	8.4	1.5	6.9	-22.5	9.9	11.2	5.4	-39.3	11.4	28.1

TABLE 13

STRATIFICATION RESULTS - TEMPERATURE (°C)

Unit (Duct A)	Total Duct Average ($\overline{X}_A$)	Inner Duct Average ($\overline{X}_a$)	Inner Duct Standard Deviation (σ)	$\overline{X}_a - \sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a - \sigma)$	$\overline{X}_a + \sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a + \sigma)$	$\overline{X}_a - 2\sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a - 2\sigma)$	$\overline{X}_a + 2\sigma$	% Difference Between $\overline{X}_A$ and $(\overline{X}_a + 2\sigma)$
Widows Creek No. 5	183	183	3	180	-1.6	186	1.6	177	-3.3	189	3.3
Widows Creek No. 7	141	143	7	136	-3.5	150	6.4	129	-8.5	157	11.3
Gaston No. 5	141	144	7	137	-2.8	151	7.1	130	-7.8	158	12.1
Barry No. 4	159	160	8	152	-4.4	168	5.7	144	-9.4	176	10.7
Barry No. 5	119	121	6	115	-3.4	127	6.7	109	-8.4	133	11.8
Morgantown No. 1	143	143	8	135	-5.6	151	5.6	127	-11.2	159	11.9
Navajo No. 1	145	146	12	134	-7.6	158	9.0	122	-15.9	170	17.2

TABLE 13 (Cont'd.)

STRATIFICATION RESULTS - TEMPERATURE (°C)

Unit (Duct B)	Total Duct Average ($\overline{X}_B$)	Inner Duct Average ($\overline{X}_b$)	Inner Duct Standard Deviation (σ)	$\overline{X}_b - \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - \sigma$)	$\overline{X}_b + \sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + \sigma$)	$\overline{X}_b - 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b - 2\sigma$)	$\overline{X}_b + 2\sigma$	% Difference Between $\overline{X}_B$ and ($\overline{X}_b + 2\sigma$)
Widows Creek No. 5	172	171	3	168	-2.3	174	1.2	165	-4.1	177	2.9
Widows Creek No. 7	134	139	9	130	-3.0	148	10.4	121	-9.7	157	17.2
Gaston No. 5	121	125	8	117	-3.3	133	9.9	109	-9.9	141	16.5
Barry No. 4	131	130	6	124	-5.3	136	3.8	118	-9.9	142	8.4
Barry No. 5	117	120	10	110	-6.0	130	11.1	100	-14.5	140	19.7
Morgantown No. 1	138	137	8	129	-6.5	145	5.1	121	-12.3	153	10.9
Navajo No. 1	129	132	1	131	1.6	133	3.1	130	0.8	134	3.9

TABLE 13 (Cont'd.)

STRATIFICATION RESULTS - TEMPERATURE (°C)

Unit (Duct C)	Total Duct Average ($\overline{X}_C$)	Inner Duct Average ($\overline{X}_c$)	Inner Duct Standard Deviation (σ)	$\overline{X}_c - \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - \sigma$)	$\overline{X}_c + \sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + \sigma$)	$\overline{X}_c - 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c - 2\sigma$)	$\overline{X}_c + 2\sigma$	% Difference Between $\overline{X}_C$ and ($\overline{X}_c + 2\sigma$)
Navajo No. 1	130	133	5	128	-1.5	138	6.2	123	-5.4	143	10.0

Unit (Duct D)	Total Duct Average ($\overline{X}_D$)	Inner Duct Average ($\overline{X}_d$)	Inner Duct Standard Deviation (σ)	$\overline{X}_d - \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - \sigma$)	$\overline{X}_d + \sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + \sigma$)	$\overline{X}_d - 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d - 2\sigma$)	$\overline{X}_d + 2\sigma$	% Difference Between $\overline{X}_D$ and ($\overline{X}_d + 2\sigma$)
Navajo No. 1	154	156	2	154	0.0	158	2.6	152	-1.3	160	3.9

In the cases where $\overline{X} \pm 2\sigma$ differed significantly from the total duct average, in most instances a substantial reduction in this difference could be obtained by extracting a composite sample from the inner portion of the duct cross section. Consider the following illustrations:

1. E.C. Gaston Unit 5 - Duct A

For the SO_2 measurements, $\overline{X}_{SO_2} \pm 2\sigma$ differed from the total duct SO_2 average by -39.5 to 47.9%. This means that if single samples are extracted from the inner portion of the duct approximately 95% of these samples will show a SO_2 concentration between 703 and 1719 ppm. The total duct SO_2 average concentration is 1162. Therefore, in many cases it can be expected that a single sample will not result in a truly representative sample. Our calculations indicate that if n 3-point composite samples are extracted and analyzed, it can be expected that 95% of them will show a SO_2 concentration of 864 to 1208 ppm. These figures are clearly much nearer to the actual SO_2 concentration in the flue gas (although still inadequate for monitoring purposes).

2. Barry Unit 5 - Duct A

For the O_2 measurements, $\overline{X}_{O_2} \pm 2\sigma$ differed from the total duct average by -44.0 to 28.0%. Our calculations indicate that if 3-point composite samples are used rather than single point samples, approximately 95% of the samples will range between -24.0 and 0.0% of the total duct O_2 average.

Therefore, it is recommended that composite sampling probes be used. At least two probes of this type should be used per duct and they should be constructed so that samples are taken from zones of "equal areas" within the inner 50% of the duct. Results of the in-stack test indicate that stack conditions are extremely uniform and that this should be the preferred sampling location provided that practical accessibility to such a sampling location is available. Tables 14 and 15 show the results of the in-stack tests performed on Navajo Unit No. 1.

Based on experience obtained from this program and other Exxon government sponsored research, the following sampling system is recommended:

After the sample is extracted from the duct, it should pass through lines heated high enough to prevent condensation before being passed through a heated filter for a final particulate cleanup. The sample then would pass through a permeation drying tube for moisture removal before being sent to the analytical equipment. The line after the dryer would not have to be heated and should be made of an inert material, preferably Teflon. It is also recommended that a vent be included before the analytical equipment so that a high flow rate could be used. This would reduce the residence time of the gas in the lines and restrict any possible SO_2 reactions.

TABLE 14

NAVAJO UNIT 1 (IN STACK AT 725 MW) TEST RESULTS

	Total Duct Average ($\overline{X}_T$)	Inner Duct Average ($\overline{X}$)	Inner Duct Standard Deviation (σ)	$\overline{X} - \sigma$	% Difference Between $\overline{X}_T$ and ($\overline{X} - \sigma$)	$\overline{X} + \sigma$	% Difference Between $\overline{X}_T$ and ($\overline{X} + \sigma$)	$\overline{X} - 2\sigma$	% Difference Between $\overline{X}_T$ and ($\overline{X} - 2\sigma$)	$\overline{X} + 2\sigma$	% Difference Between $\overline{X}_T$ and ($\overline{X} + 2\sigma$)
SO_2 (ppm)	553	549	27	522	-5.6	576	4.2	495	-10.5	603	9.0
NO (ppm)	294	295	21	274	-6.8	316	7.5	253	-13.9	337	14.6
CO_2 (%)	14.6	14.6	0.8	13.8	-5.5	15.4	5.5	13.0	-11.0	16.2	11.0
O_2 (%)	6.2	6.2	0.2	6.0	-3.2	6.4	3.2	5.8	-6.5	6.6	6.5
Velocity (M/S)	31.5	33.0	0.7	32.3	2.5	33.7	7.0	31.6	0.3	34.4	9.2
Temperature (°C)	139	139	2	137	-1.4	141	1.4	135	-2.9	143	2.9

TABLE 15

NAVAJO UNIT 1 (IN STACK TEST AT 800 MW) TEST RESULTS

	Total Duct Average ($\overline{X}_T$)	Inner Duct Average ($\overline{X}$)	Inner Duct Standard Deviation (σ)	$\overline{X} - \sigma$	% Difference Between $\overline{X}_T$ and $(\overline{X} - \sigma)$	$\overline{X} + \sigma$	% Difference Between $\overline{X}_T$ and $(\overline{X} + \sigma)$	$\overline{X} - 2\sigma$	% Difference Between $\overline{X}_T$ and $(\overline{X} - 2\sigma)$	$\overline{X} + 2\sigma$	% Difference Between $\overline{X}_T$ and $(\overline{X} + 2\sigma)$
SO_2 (ppm)	554	551	14	537	-3.1	565	2.0	523	-5.6	579	4.5
NO (ppm)	299	299	14	285	-4.7	313	4.7	271	-9.4	327	9.4
CO_2 (%)	15.5	15.5	0.2	15.3	-1.3	15.7	1.3	15.1	-2.6	15.9	2.6
O_2 (%)	6.2	6.3	0.3	6.0	-3.2	6.6	6.5	5.7	-8.1	6.9	11.3
Velocity (M/S)	41.5	43.9	2.2	41.7	-0.5	46.1	11.1	39.5	-4.8	48.3	16.4
Temperature (°C)	149	149	1	148	-0.7	150	0.7	147	-1.3	151	1.3

3. FIELD STUDY PLANNING AND PROCEDURES

3.1 Power Plant Boiler Selection

The selection of representative power plant boilers for the study of stratification was an extremely important first step in our program. Exxon's approach to this task was patterned after our successful practice in selecting power plant boilers for our continuing field studies of combustion modifications to control NO_x and other pollutant emissions (1,2,3). Planning was coordinated in cooperation with the EPA Project Officer. The major factors guiding this activity were the following:

1. Boilers representative of current design practices of major manufacturers had to be selected. A list of the units tested and the start-up date of each unit are shown in Table 16.

2. The full cooperation of electric utility boiler owner-operators had to be assured for conducting a successful test program.

Operationally, our planning activity consisted of the following steps:

1. Exxon reviewed the suitability of the candidate boilers.

2. Exxon contacted boiler operators whose units had been selected on a tentative basis to arrange initial meetings.

3. Exxon met with the boiler operators. The objectives of our test program were discussed, and the cooperation of the boiler operators was requested.

4. While visiting the individual utility companies, tentative testing schedules were arranged.

5. It was agreed with the cooperating utilities that Exxon would confirm the test schedule, and transmit to them detailed test program designs.

We carried out this program by meshing the schedule of the stratification study with that of our continuing field test program on emission control under the sponsorship of the Combustion Research Branch of the Industrial and Environmental Research Laboratory-EPA, RTP. This approach provided several significant advantages:

TABLE 16

UNITS TESTED IN STRATIFICATION PROGRAM AND START-UP DATE OF EACH UNIT

Unit	Start-Up Date
Widows Creek Unit 5	1954
Widows Creek Unit 7	1961
E. C. Gaston Unit 5	1974
Barry Unit 4	1969
Barry Unit 5	1971
Morgantown Unit 1	1970
Navajo Unit 1	1974

- Some of the boilers selected for stratification measurements were also tested for additional measurements with our standard sample probing system upstream of the air heaters.
- Travel costs were minimized and the time required for development of the sampling-analytical equipment for the stratification studies were significantly reduced.
- The contacts and discussions with power plant and other utility company personnel were held at the same time as those for our emission control field studies. Again, significant improvements in efficiency, and corresponding savings resulted.

3.2 Test Procedures

3.2.1 Gaseous Sampling and Analysis

The objective of obtaining reliable gaseous emission data in field testing boilers requires a sophisticated sampling system. The basic sampling and analytical system used in this program has already been described in detail in the Exxon Research and Engineering Company Report, "Systematic Field Study of NO_x Emission Control Methods for Utility Boilers" (2).

For the present program, modifications were made in the system to further assure reliable, accurate analyses. The major change was to replace the refrigerated water knock-out in the sample line with a permeation type drying tube. This was done to assure that the sample gas was virtually moisture free. Figure 1 is a schematic diagram of the configuration of the gaseous sampling and analytical system used in this study. In running the stratification tests, the gas samples were withdrawn from the duct through a sintered metal filter which removed all particulates greater than 1 to 1½ microns. A heated ceramic core filter was affixed to the end of the gas sampling tube followed by a Perma Pure Products, Inc. permeation drying tube which operates on the permeation distillation principle. All water in the flue gas sample was removed at this point, thus decreasing the probability of inaccuracy of the results due to partial absorption of the critical gaseous species in the water which may condense beyond this point. The permeation drying tubes were purged continuously with either bottled nitrogen or plant air to remove the water in the gas sample. Usually, the van was located 100 to 200 feet from this point and the gas stream flowed through Teflon lines throughout this distance.

As in our previous field test programs, our analytical van was equipped with a Thermo-Electron chemiluminescence instrument for NO and NO_x measurements, Beckman non-dispersive infrared analyzers to measure NO, CO, CO_2 and SO_2, a non-dispersive ultraviolet analyzer for NO_2 measurement, a polarographic analyzer for O_2 and a flame ionization analyzer for hydrocarbon analysis. Data analysis was done using the NO measurements obtained using the chemiluminescence analyzer and, in general, measurements obtained using the NDIR analyzer agreed reasonably well. The measuring ranges of these continuous analyzers are listed in Table 17. To assure accurate analyses, the instruments were calibrated before each test with calibration gases in appropriate concentrations with N_2 as the carrier gas. "S" type pitot tubes were used to measure the flue gas velocity.

Special probes were fabricated to obtain the gas stratification data required for this study. These probes sampled near isokinetically, and ensured that sampling would not occur superisokinetically. Isokinetic sampling is not as important for gaseous sampling as it is for particulates. However, since the objective of the program was to determine the extent of flue gas stratification in power plant boiler ducting, care had to be taken not to disturb stratification conditions if they existed. Therefore, in

FIGURE 1

EXXON RESEARCH STRATIFICATION SAMPLING SYSTEM

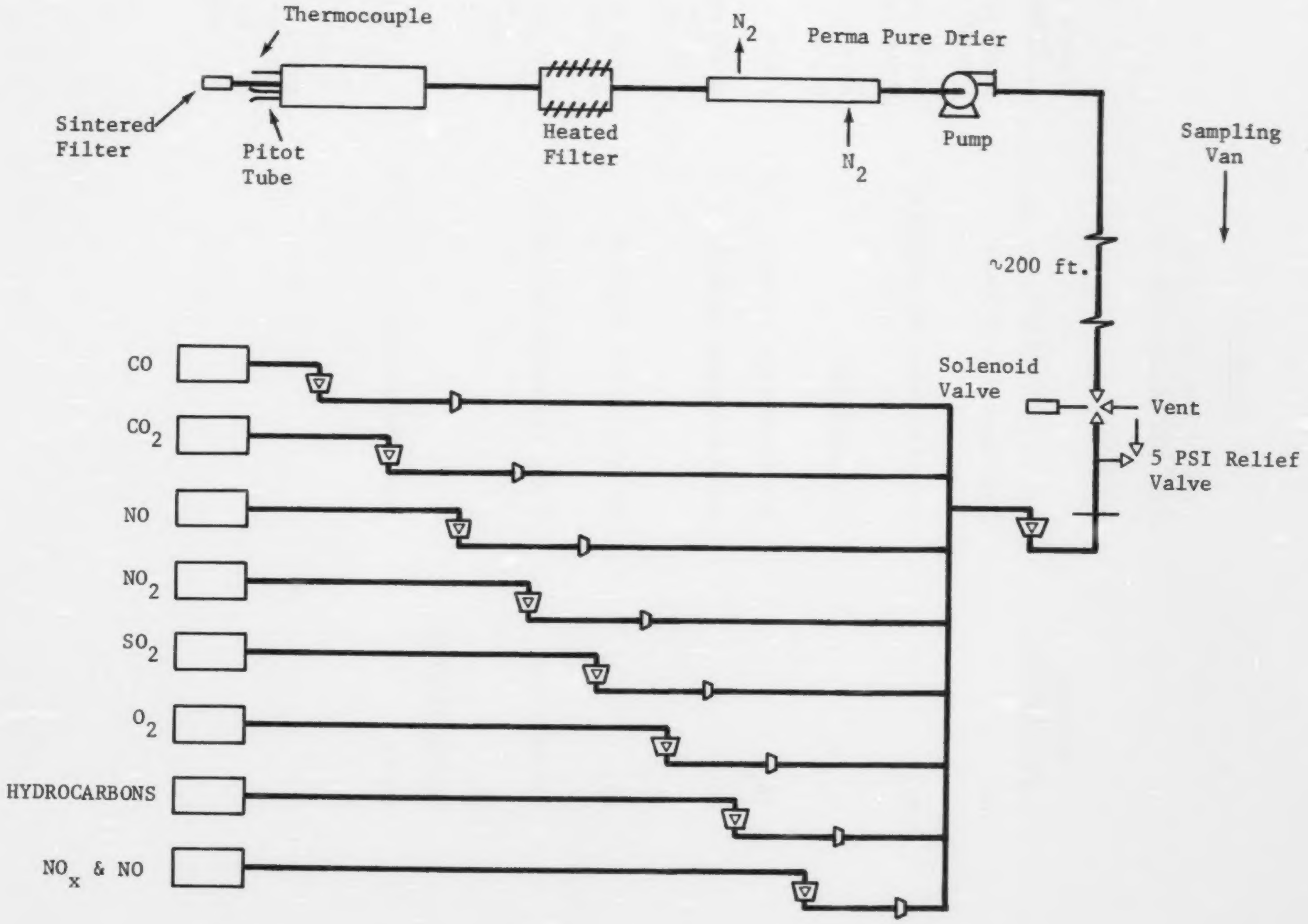

Thermocouple
Sintered Filter
Pitot Tube
Heated Filter
N_2
Perma Pure Drier
N_2
Pump
Sampling Van
~200 ft.
Solenoid Valve
Vent
5 PSI Relief Valve
CO
CO_2
NO
NO_2
SO_2
O_2
HYDROCARBONS
NO_x & NO

TABLE 17

CONTINUOUS ANALYTICAL INSTRUMENTS IN EXXON VAN

Beckman Instruments	Technique	Measuring Range
NO	Non-dispersive infrared	0-400 ppm 0-2,000 ppm
NO_2	Non-dispersive ultraviolet	0-100 ppm 0-400 ppm
O_2	Polarographic	0-5% 0-25%
CO_2	Non-dispersive infrared	0-20%
CO	Non-dispersive infrared	0-200 ppm 0-1,000 ppm 0-23,600 ppm
SO_2	Non-dispersive infrared	0-600 ppm 0-3,000 ppm
Hydrocarbons	Flame ionization detection	0-10 ppm 0-100 ppm 0-1,000 ppm
Thermo Electron		
NO/NO_x	Chemiluminescence	0-2.5 ppm 0-10.0 ppm 0-25 ppm 0-100 ppm 0-250 ppm 0-1,000 ppm 0-2,500 ppm 0-10,000 ppm

conducting the stratification measurement program for gaseous species, it was important to assure that the gas samples were not withdrawn at a super-isokinetic rate so that the sampling tube itself would not act as a "vacuum cleaner", and upset stratification patterns in the area of the sampling nozzle. Subisokinetic sampling rates would not be expected to disturb stratification patterns. The probes were built in accordance with the details shown in Figures 2-7. Each probe consisted of an "S" type pitot tube for the measurement of gas velocity, a thermocouple for measuring duct gas temperature and a 3/8 inch stainless steel gas sampling tube all encased in a 1-3/4 inch stainless steel pipe for rigidity. The basic probe was 12 feet long with an 8 foot extension for use in larger ducts.

The design of the stratification probes was coordinated with EPA's Industrial and Environmental Research Laboratory, Process Measurement Branch. The calibration of the "S" type pitot tubes was done in the wind-tunnel of EPA's Combustion Research Laboratory at Research Triangle Park.

Reproduced from best available copy.

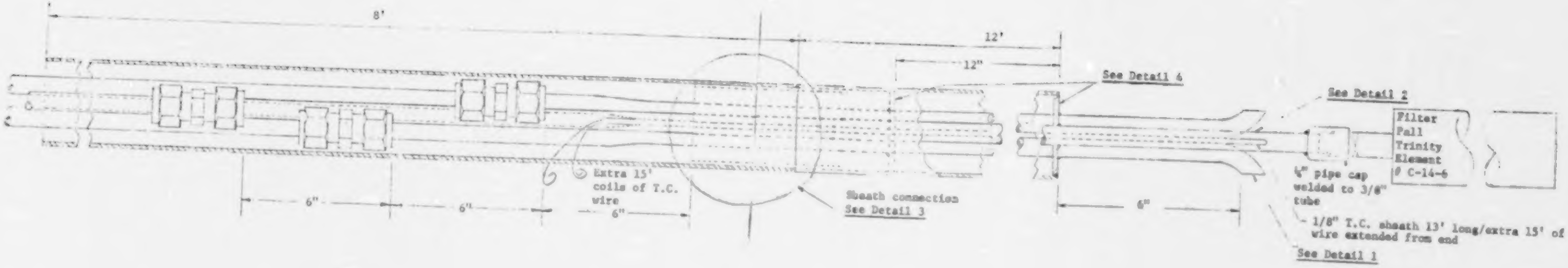
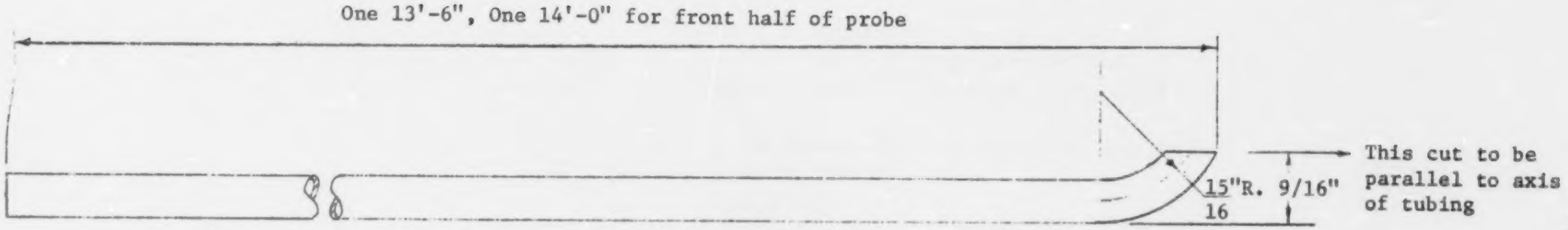

8'
12'
12"
See Detail 6
See Detail 2
Filter
Pall
Trinity
Element
ø C-14-6
Extra 15' coils of T.C. wire
6"
6"
6"
Sheath connection
See Detail 3
6"
¼" pipe cap welded to 3/8" tube
1/8" T.C. sheath 13' long/extra 15' of wire extended from end
See Detail 1

FIGURE 2

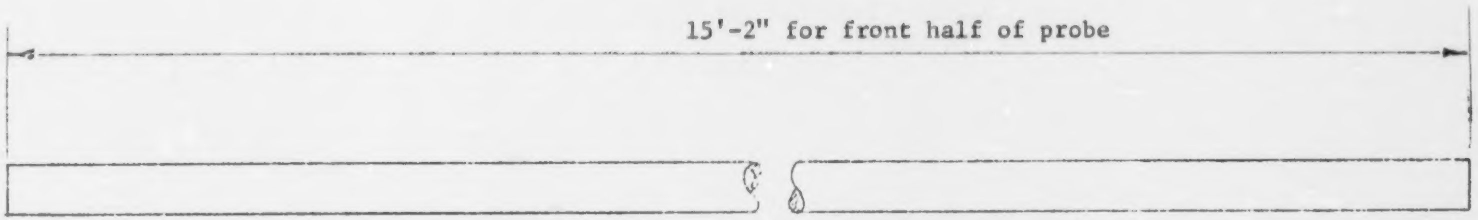
SCHEMATIC OF STRATIFICATION SAMPLING PROBE


One 13'-6", One 14'-0" for front half of probe
15/16"R.
9/16"
This cut to be parallel to axis of tubing

Pitot Tube Detail 1 - 2 Req'd 3/8" 304 S.S. tubing .035 wall

FIGURE 3

STRATIFICATION SAMPLING PROBE - DETAIL 1


15'-2" for front half of probe

Detail 2

Sample taking tube
1 required 304 S.S. tubing .035 wall

Note: Supply 3 pieces 7'-6" long
of 3/8" S.S. tubing for
extension

FIGURE 4

STRATIFICATION SAMPLING PROBE - DETAIL 2

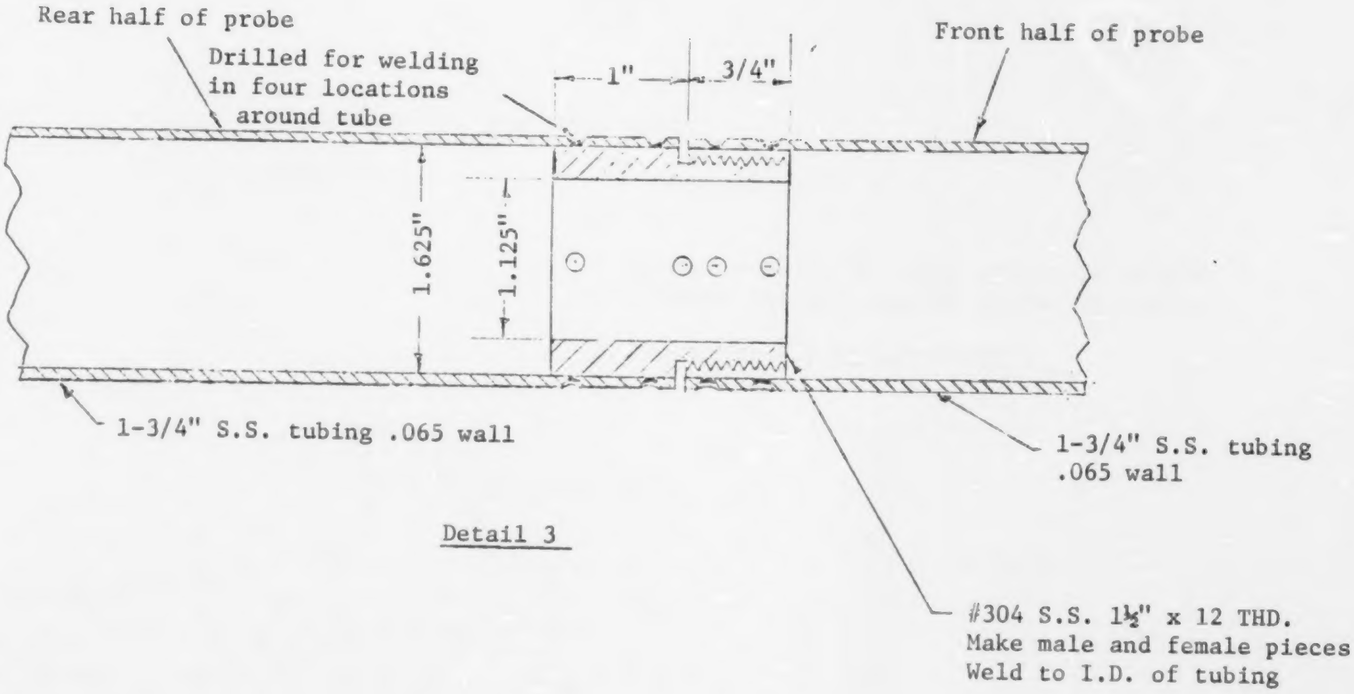
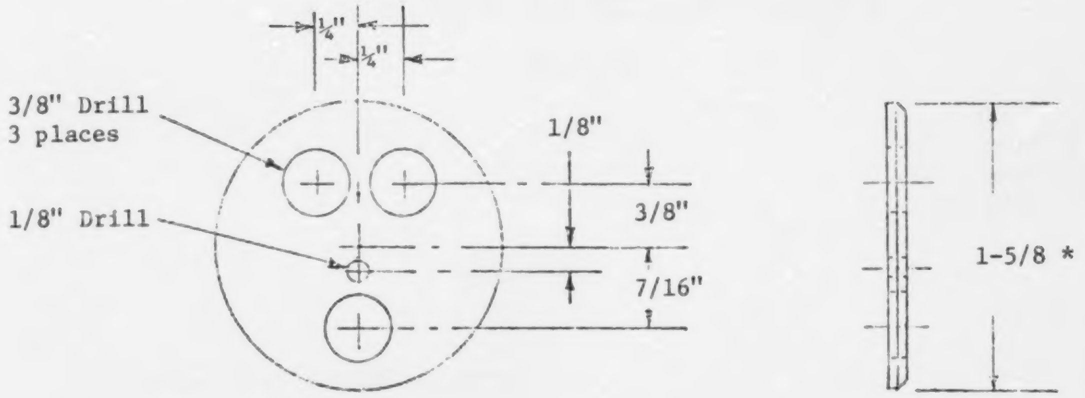

Rear half of probe
Drilled for welding
in four locations
around tube
1"
3/4"
Front half of probe
1.625"
1.125"
1-3/4" S.S. tubing .065 wall
1-3/4" S.S. tubing
.065 wall
Detail 3
#304 S.S. 1½" x 12 THD.
Make male and female pieces
Weld to I.D. of tubing

FIGURE 5

STRATIFICATION SAMPLING PROBE - DETAIL 3


¼"
¼"
3/8" Drill
3 places
1/8" Drill
1/8"
3/8"
7/16"
1-5/8 *

All holes to fit tubing snuggly

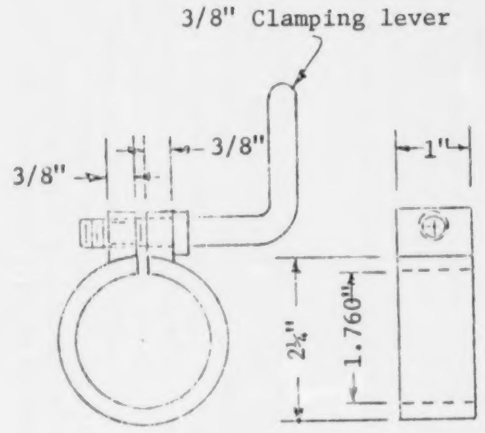
* Chamber one for welding to end of sheath.
Second disk to be slide fitted in sheath.

Detail 4

2 required 304 S.S. 1/8" thick.

FIGURE 6

STRATIFICATION SAMPLING PROBE - DETAIL 4


3/8" Clamping lever
3/8"
3/8"
1"
2¼"
1.760"

Detail 5

1 Required #304 S.S.
½"-1"

Safety Clamp

FIGURE 7

STRATIFICATION SAMPLING PROBE - DETAIL 5

3.2.2 Sampling Location Selection

For our stratification test program, the selection of sampling locations and the number of sampling points were based on attempts to obtain representative gas samples. Usually, the preferred locations for sampling and monitoring are towards the end of long flow paths where the gases have had an opportunity to mix thoroughly, and velocity patterns are more uniform. The criteria used to determine this preferred sampling location is that it be located at least eight stack or duct diameters downstream and two diameters upstream from any bend, expansion, contraction, valve, fitting, or any other flow disturbance. For rectangular ducts, the equivalent diameter is calculated from the expression:

$$\text{equivalent diameter} = 2(\text{length} \times \text{width})/(\text{length} + \text{width})$$

Unfortunately from this standpoint, the lengths of flue ducts on most power plant boilers are kept as short as possible to minimize overall investment costs. Most ducts are fitted into confined spaces requiring bends and expansion sections which do not lend themselves to obtaining representative gas samples.

In all of our tests, sampling was done downstream of the air preheater. One of the disadvantages of sampling downstream of the air preheater is that an air leakage factor is introduced. However, flue gas temperature (about 350°F as opposed to 600-750°F upstream of the air preheater) and pressure conditions at downstream locations offer advantages for testing and monitoring.

After determining the sampling locations, provisions must be made to traverse the duct. Guidelines to determine the number of traverse points required to obtain a representative sample are specified in the Federal Register (5). The number is based on the location of the sampling point with respect to upstream and downstream flow disturbances as indicated above. Since the duct configurations on most of the units tested were not ideal, it was usually necessary to sample at a maximum number of traverse points. Also, on some of the boilers tested the number and spacing of sampling ports frequently prevented obtaining representative samples in accordance with the procedures outlined in the Federal Register.

As can be seen from Table 18, in most cases we were not able to adhere strictly to EPA guidelines. In the case of our test on Widows Creek Unit 5 where a significant deviation occurred because of an insufficient number of sampling ports, requests were made to plant personnel to have additional ports installed. The request was refused because, due to manpower shortage, utility personnel were not available for installing the additional ports. Figures 8-14 show the location of the sampling ports on the units tested and Figures 15-26 show the number and location of sampling points.

TABLE 18

SUMMARY OF SAMPLING LOCATIONS AND NUMBER OF SAMPLING POINTS

Unit	Sampling Location	Equivalent Diameter (ft)	Distance from Nearest Disturbance (ft)		Required Number of Sampling Points (EPA Guidelines)	Actual Number of Sampling Points
			Downstream	Upstream		
Widows Creek Unit 5	Downstream of rotary air preheater, just upstream of I.D. fan	11.6	~1½	~5½	48	15
Widows Creek Unit 7	Downstream of rotary air preheater, just upstream of electrostatic precipitator	15.0	~35	~4	48	48
E.C. Gaston Unit 5	Just downstream of the rotary air preheater	13.5	Sampling ports located at the start of an expansion section (see Figure 10)		48	30
Barry Unit 4	Downstream of electrostatic precipitator, just upstream of stack	15.3	Sampling ports located at the end of a compression section immediately before a 90° bend (see Figure 11)		48	30
Barry Unit 5	Downstream of rotary air preheater, just upstream of electrostatic precipitator	14.7	Sampling ports located at the start of an expansion section (see Figure 12)		48	40
Morgantown Unit 1	Downstream of rotary air preheater, just upstream of electrostatic precipitator	13.4	Sampling ports located at the start of an expansion section (see Figure 13)		48	48
Navajo Unit 1	Downstream of rotary air preheater, just upstream of I.D. fan	19.5	~70	~7	48	40
Navajo Unit 1 (in stack)	350 ft. up stack	25.0	~350	~350	12	12

FIGURE 8

LOCATION OF SAMPLING PORTS -
WIDOWS CREEK UNIT 5

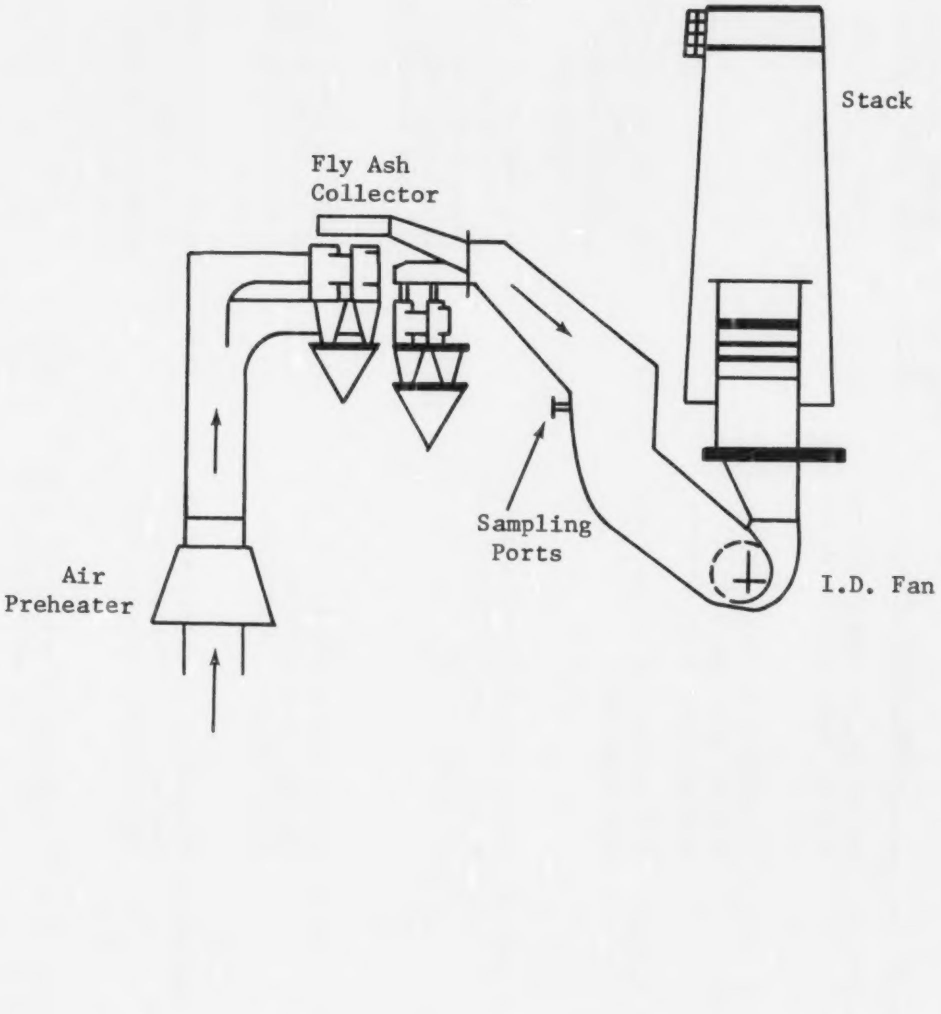

Stack
Fly Ash
Collector
Sampling
Ports
Air
Preheater
I.D. Fan

FIGURE 9

LOCATION OF SAMPLING PORTS - WIDOWS CREEK UNIT 7

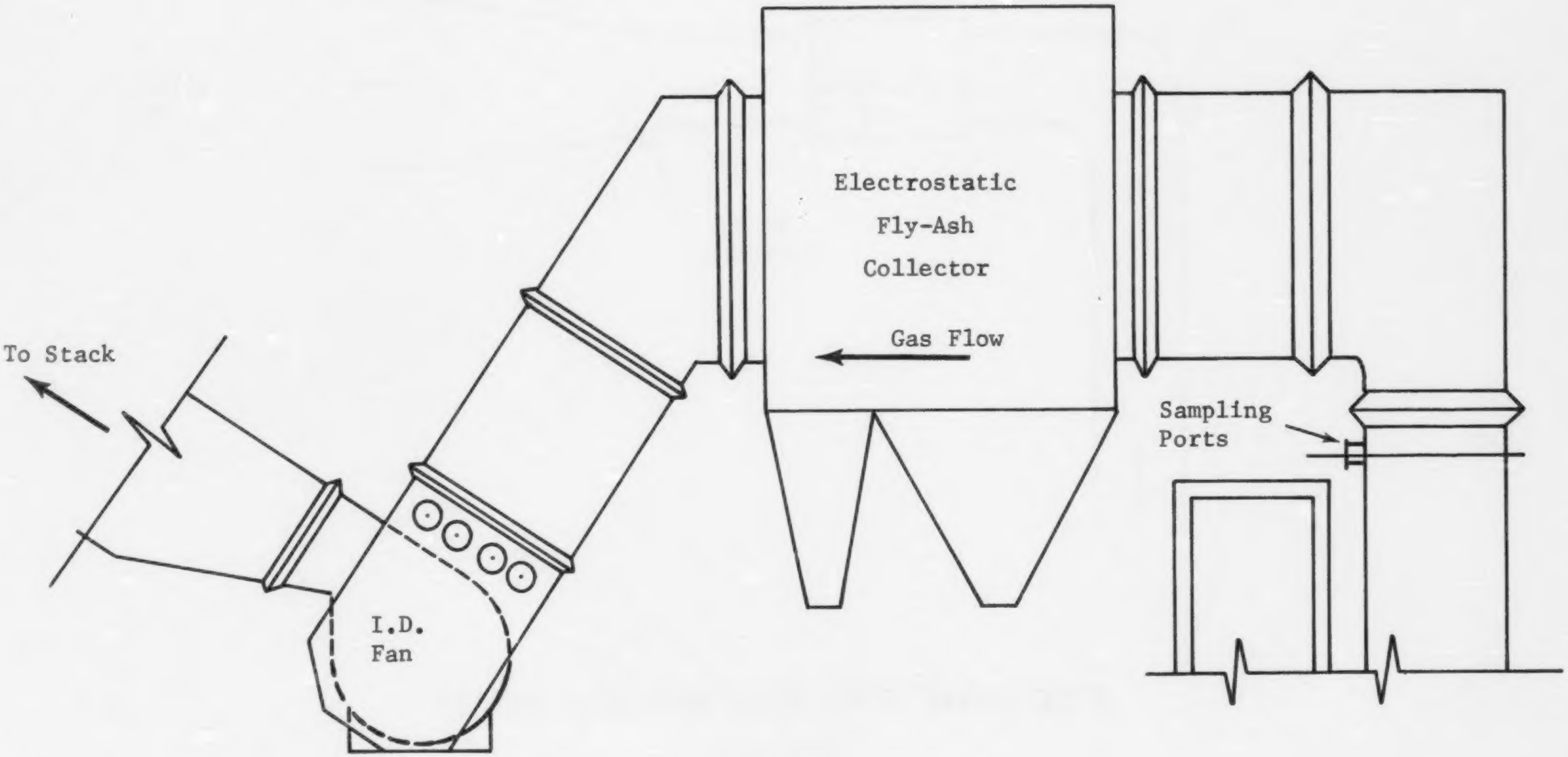

To Stack
Electrostatic
Fly-Ash
Collector
Gas Flow
Sampling
Ports
I.D.
Fan

FIGURE 10

LOCATION OF SAMPLING PORTS - E. C. GASTON UNIT 5

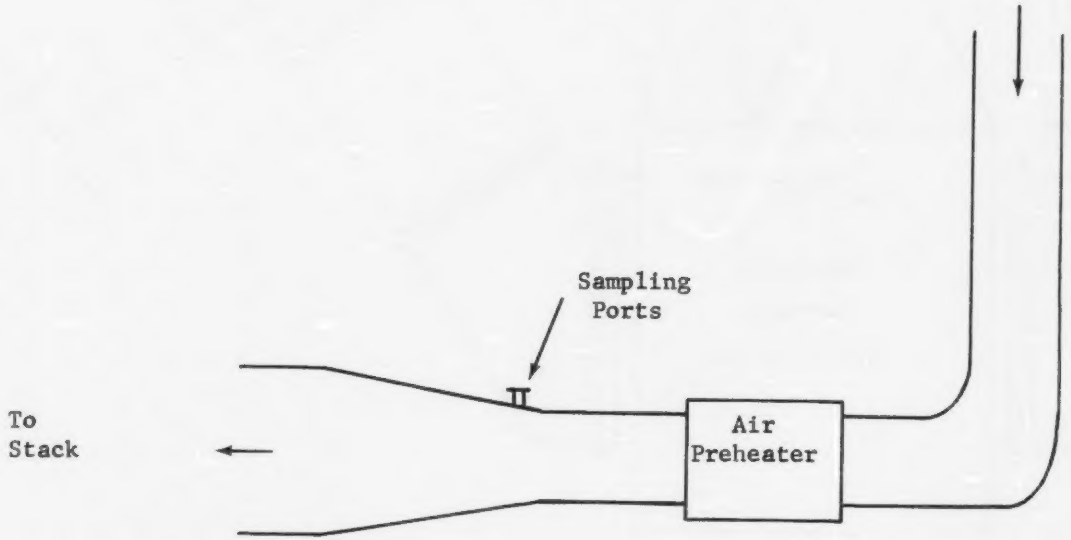

Sampling
Ports
Air
Preheater
To
Stack

FIGURE 11

LOCATION OF SAMPLING PORTS - BARRY UNIT 4

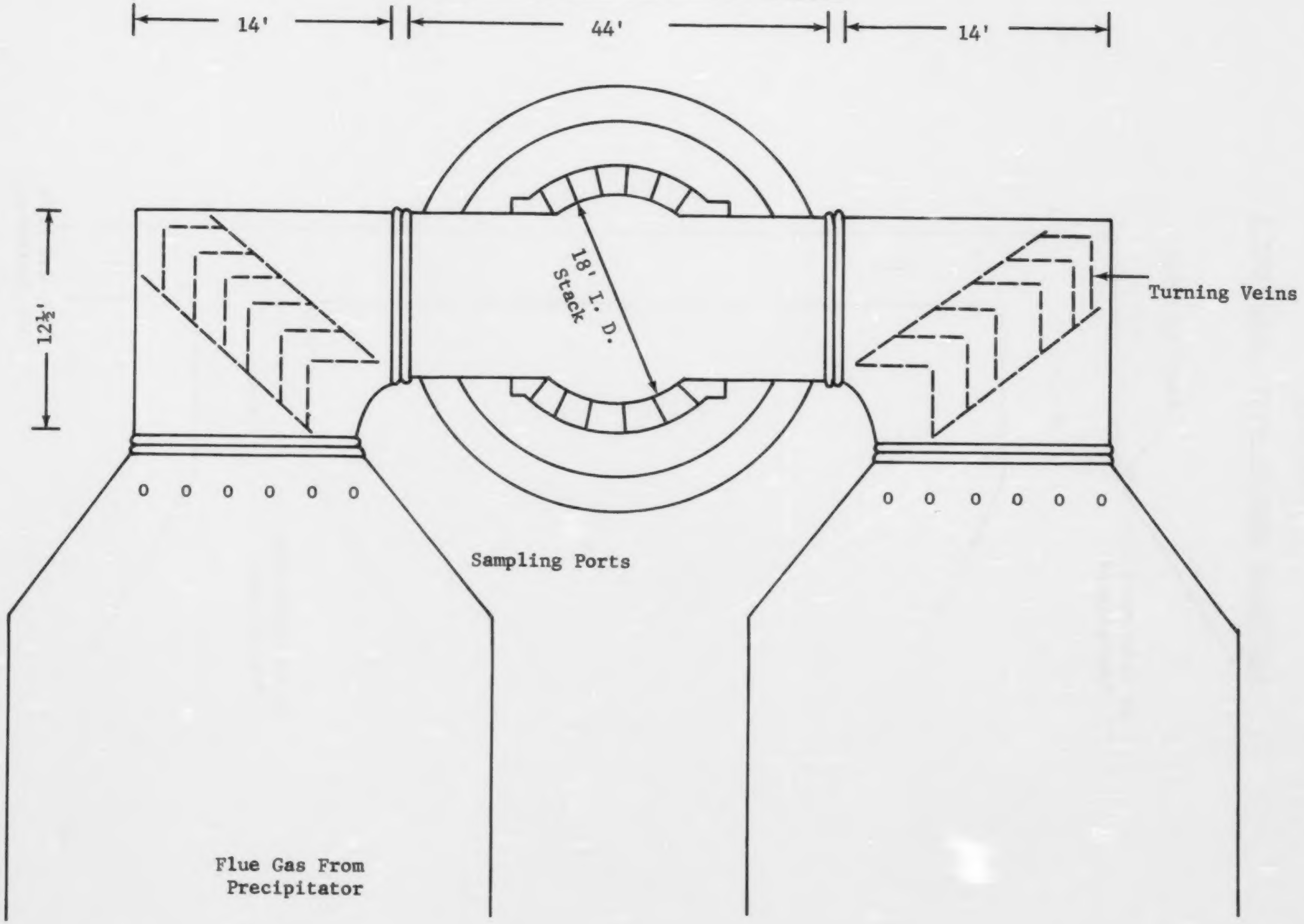

14'
44'
14'
12½'
18' I. D.
Stack
Turning Veins
Sampling Ports
Flue Gas From
Precipitator

FIGURE 12

LOCATION OF SAMPLING PORTS - BARRY UNIT 5

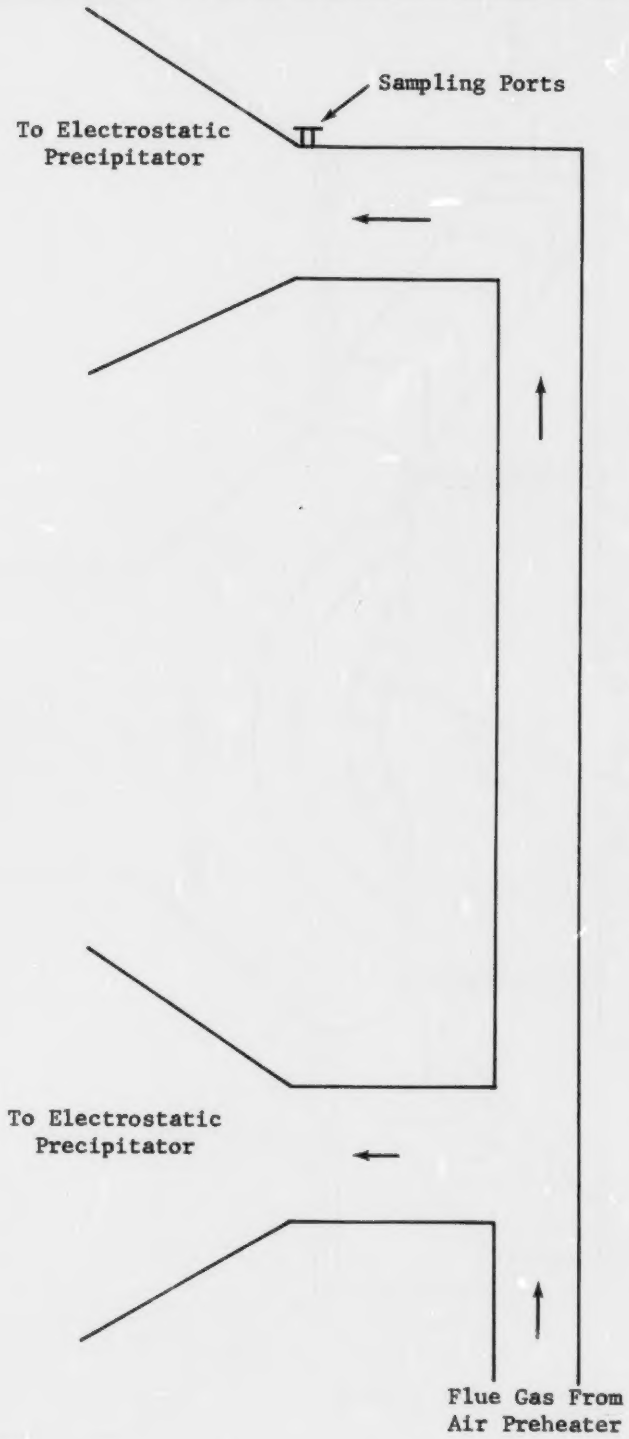

Sampling Ports
To Electrostatic Precipitator
To Electrostatic Precipitator
Flue Gas From Air Preheater

FIGURE 13

LOCATION OF SAMPLING PORTS - MORGANTOWN UNIT 1

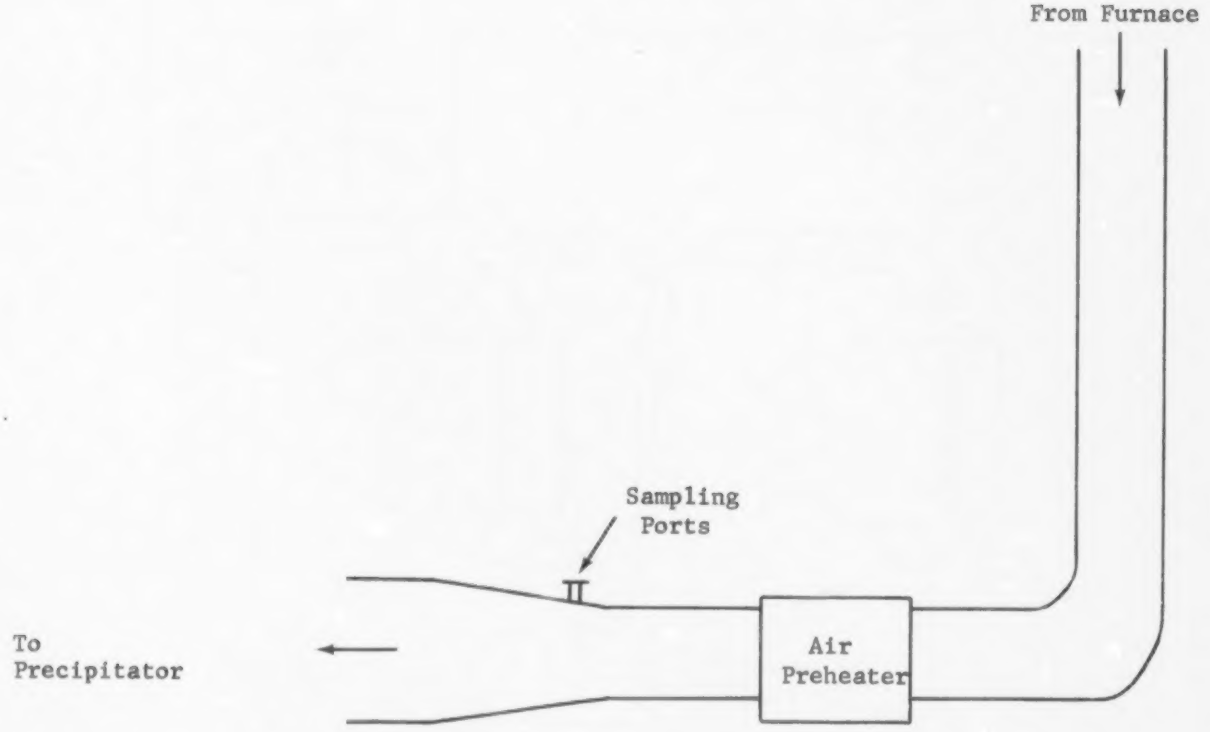

From Furnace
Sampling Ports
Air Preheater
To Precipitator

FIGURE 14

LOCATION OF SAMPLING PORTS - NAVAJO UNIT 1

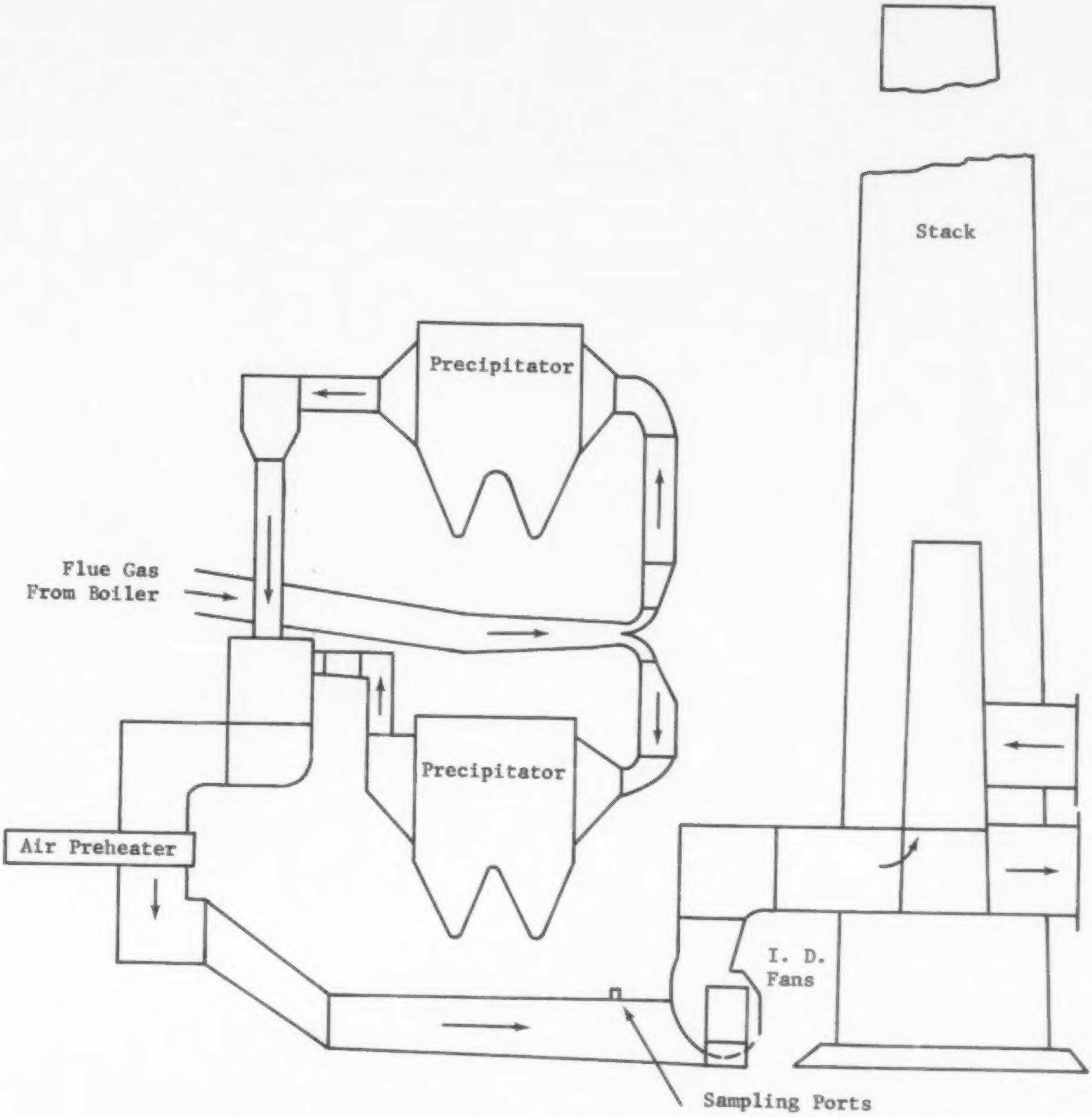
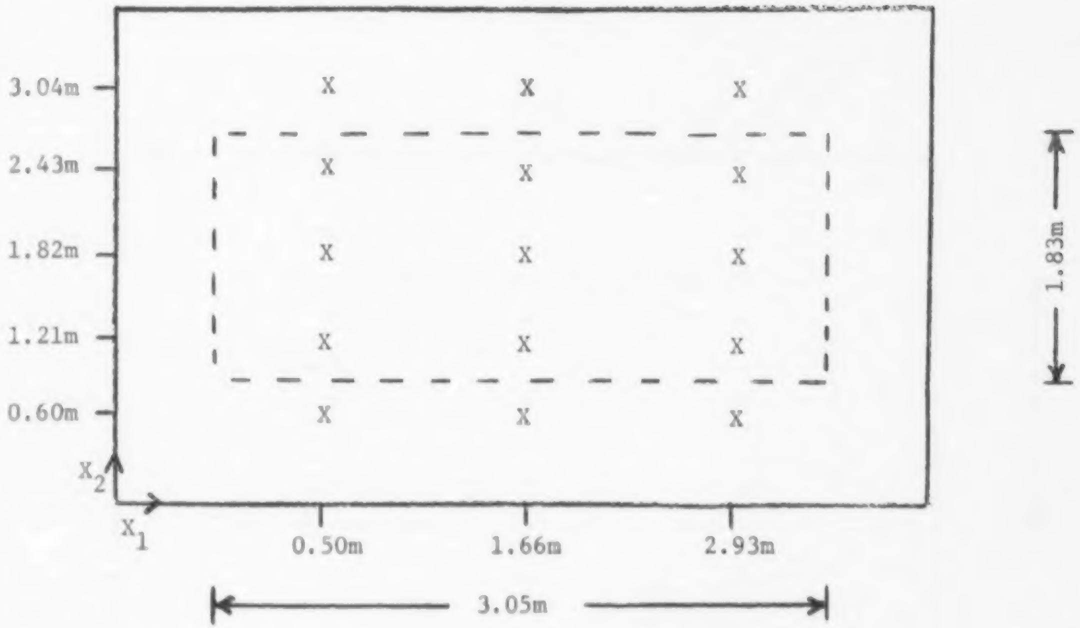

Stack
Precipitator
Flue Gas
From Boiler
Precipitator
Air Preheater
I. D.
Fans
Sampling Ports

FIGURE 15

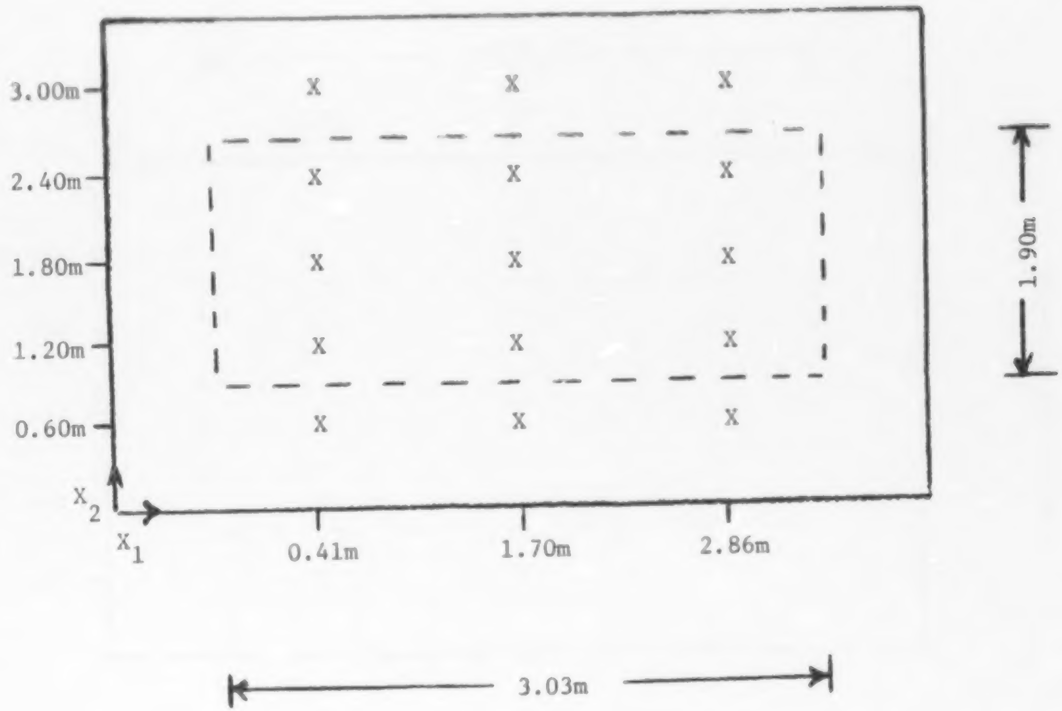
WIDOWS CREEK UNIT 5 - SAMPLING POINTS (DUCT 5A)


3.04m
2.43m
1.82m
1.21m
0.60m
X_2
X_1
0.50m
1.66m
2.93m
3.05m
1.83m

Nominal dimensions - Width - 3.66m
Depth - 3.40m

FIGURE 16

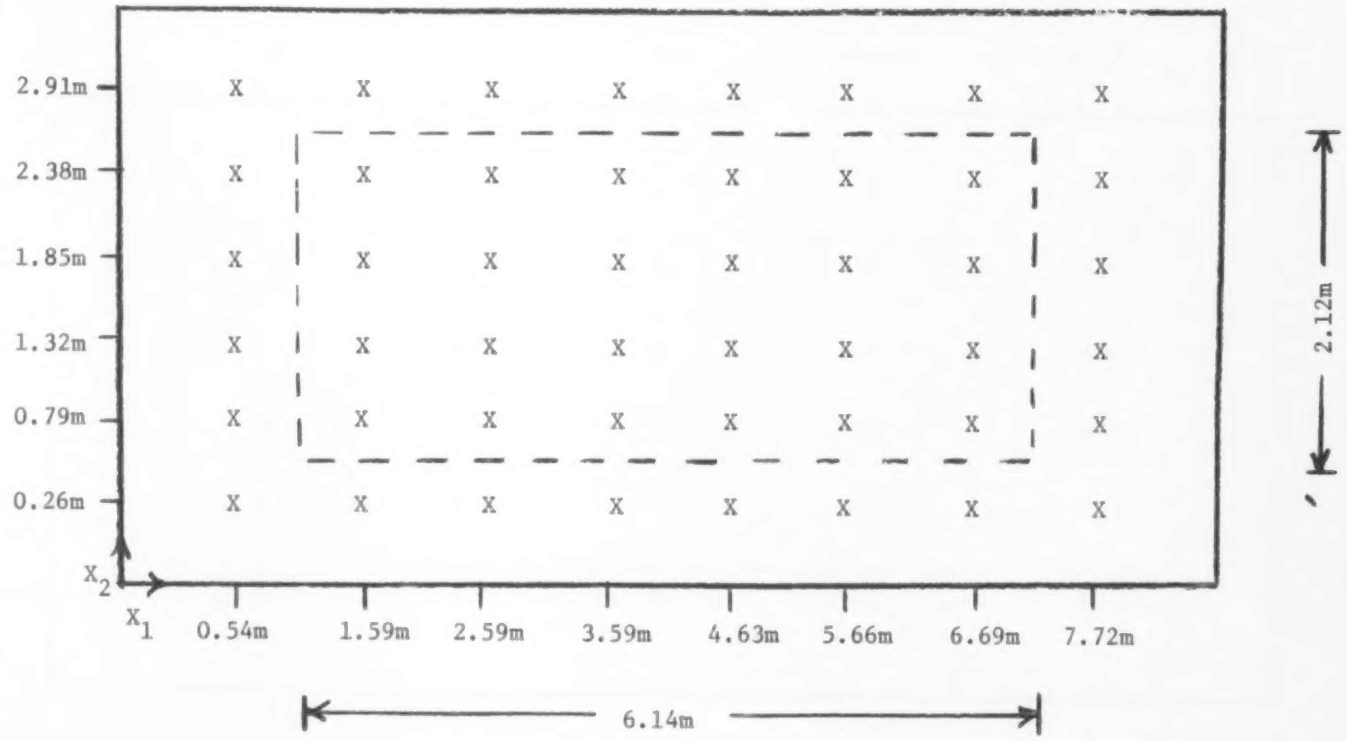
WIDOWS CREEK UNIT 5 - SAMPLING POINTS (DUCT 5B)


3.00m
2.40m
1.80m
1.20m
0.60m
X_2
X_1
0.41m
1.70m
2.86m
1.90m
3.03m
X

Nominal dimensions - Width - 3.61m
Depth - 3.35m

FIGURE 17

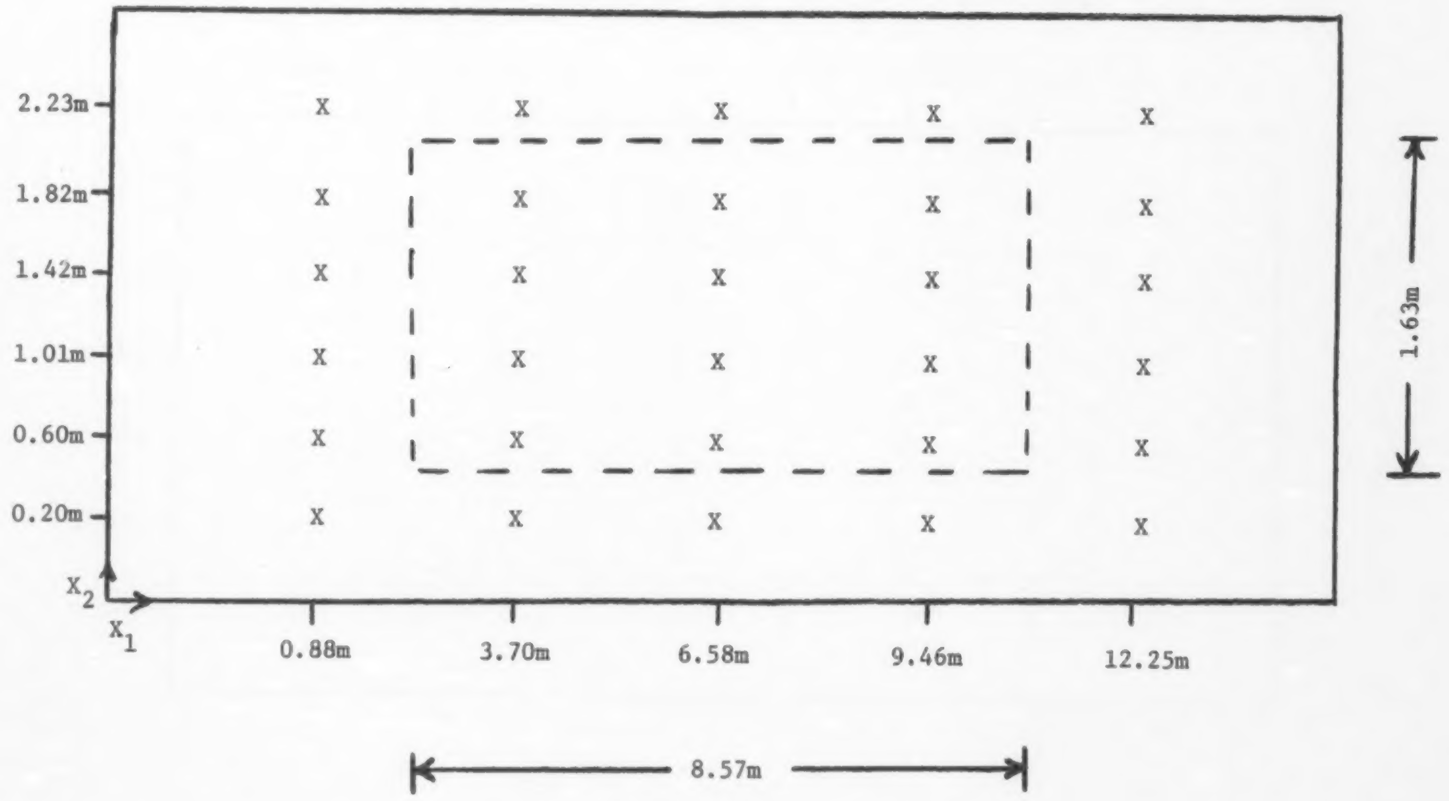
WIDOWS CREEK UNIT 7 - SAMPLING POINTS (DUCTS 7A AND 7B)


2.91m
2.38m
1.85m
1.32m
0.79m
0.26m
X_2
X_1
0.54m
1.59m
2.59m
3.59m
4.63m
5.66m
6.69m
7.72m
6.14m
2.12m

Nominal dimensions - Width - 8.23m
Depth - 3.18m

FIGURE 18

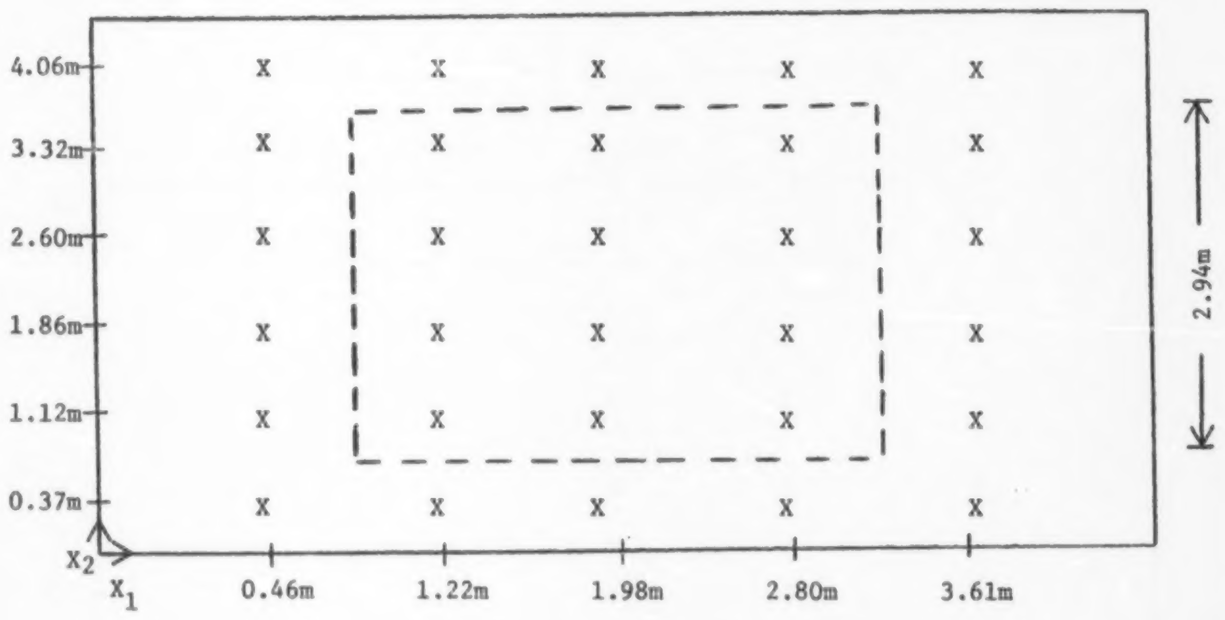
E.C. GASTON UNIT 5 - SAMPLING POINTS (DUCTS 5A AND 5B)


2.23m
1.82m
1.42m
1.01m
0.60m
0.20m
X_2
X_1
0.88m
3.70m
6.58m
9.46m
12.25m
1.63m
8.57m

Nominal dimensions - Width - 13.14m
Depth - 2.43m

FIGURE 19

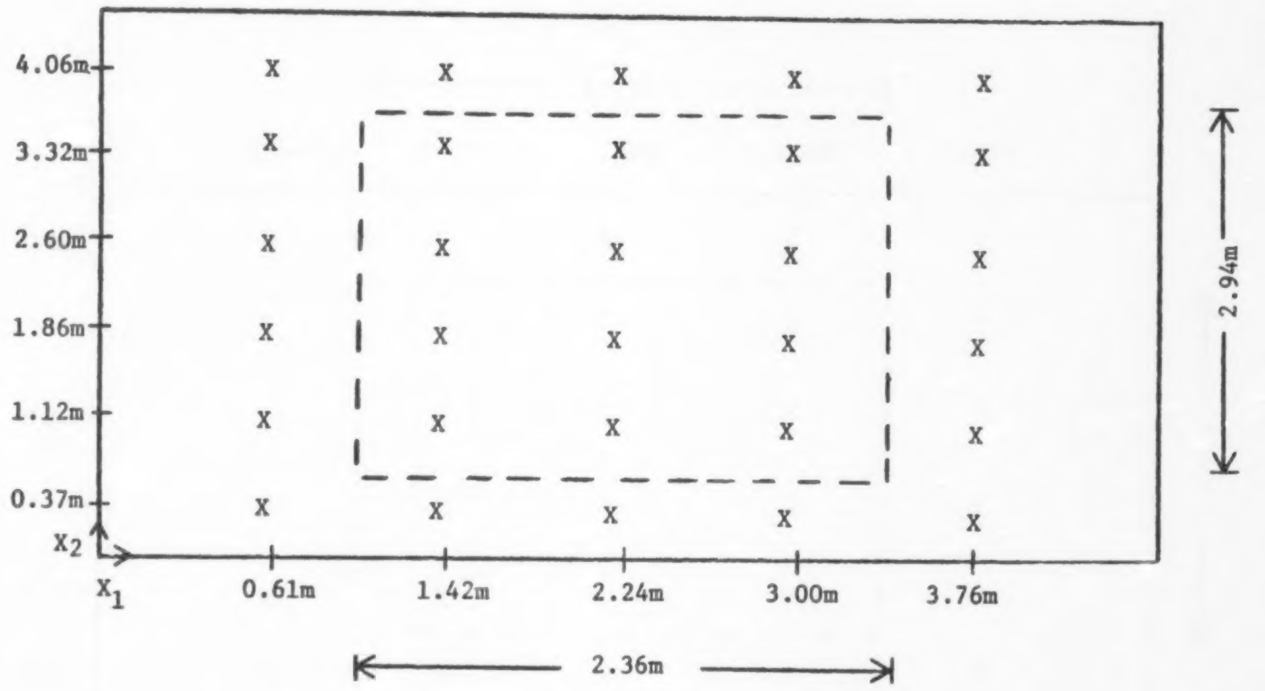
BARRY UNIT 4 - SAMPLING POINTS (DUCT 4A)


4.06m
3.32m
2.60m
1.86m
1.12m
0.37m
X_2
X_1
0.46m
1.22m
1.98m
2.80m
3.61m
2.37m
2.94m

Nominal dimensions - Width - 4.88m
Depth - 4.44m

FIGURE 20

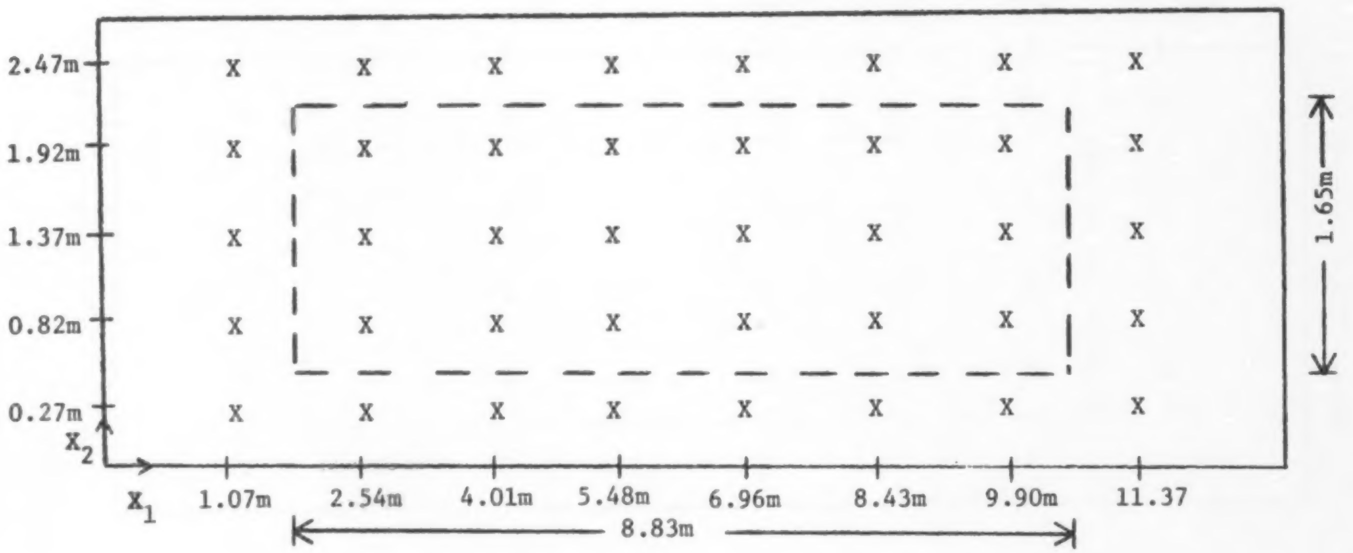
BARRY UNIT 4 - SAMPLING POINTS (DUCT 4B)


4.06m
3.32m
2.60m
1.86m
1.12m
0.37m
X_2
X_1
0.61m
1.42m
2.24m
3.00m
3.76m
2.36m
2.94m

Nominal dimensions - Width - 4.88m
Depth - 4.44m

FIGURE 21

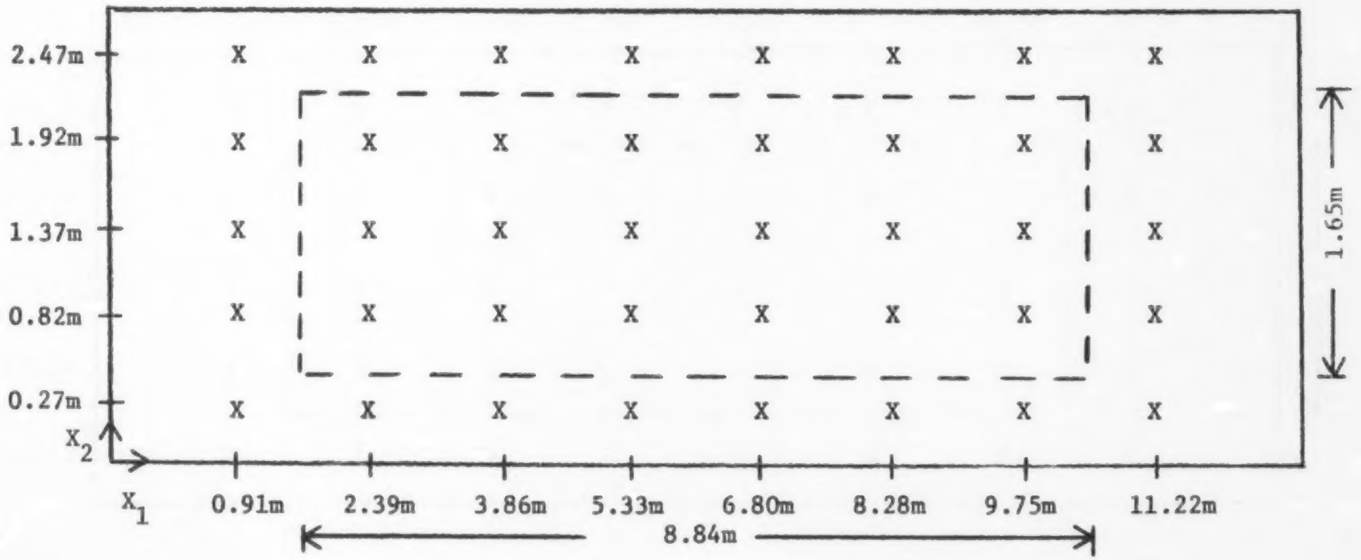
BARRY UNIT 5 - SAMPLING POINTS (DUCT 5A)


2.47m
1.92m
1.37m
0.82m
0.27m
X_2
X_1
1.07m
2.54m
4.01m
5.48m
6.96m
8.43m
9.90m
11.37
8.83m
1.65m

Nominal dimensions - Width - 12.19m
Depth - 2.74m

FIGURE 22

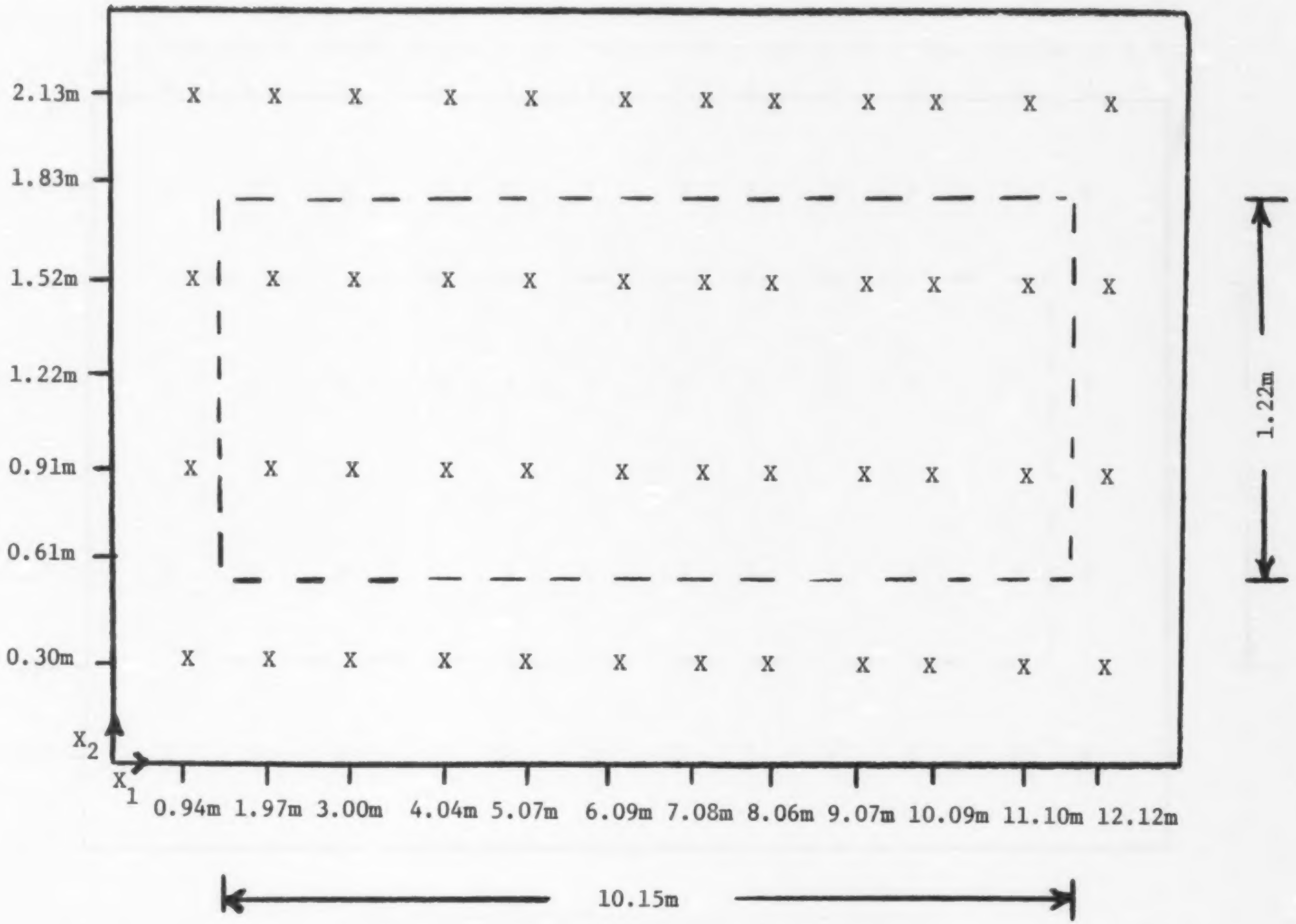
BARRY UNIT 5 - SAMPLING POINTS (DUCT 5B)


2.47m
1.92m
1.37m
0.82m
0.27m
X_2
X_1
0.91m
2.39m
3.86m
5.33m
6.80m
8.28m
9.75m
11.22m
8.84m
1.65m

Nominal dimensions - Width - 12.19m
Depth - 2.74m

FIGURE 23

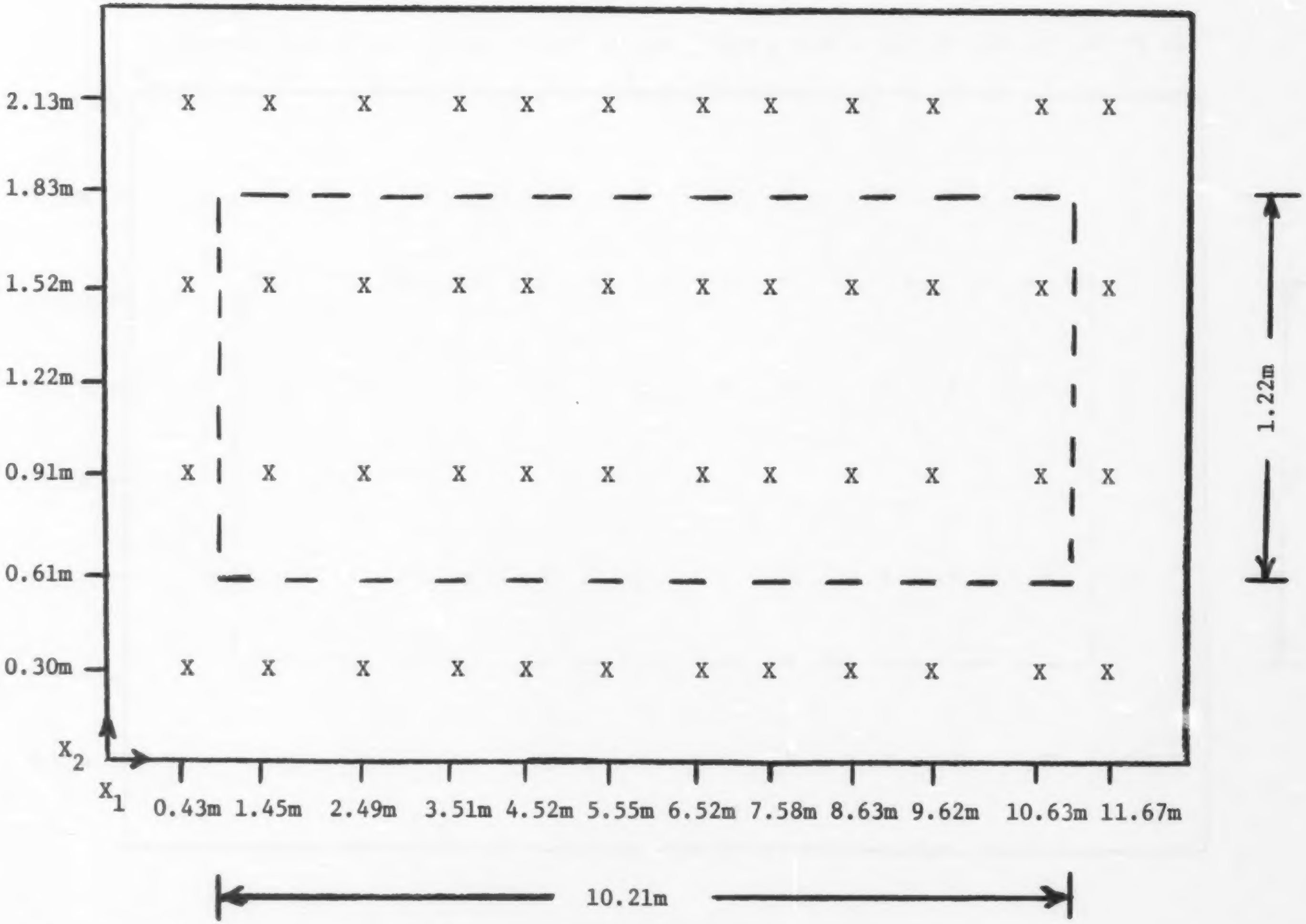
MORGANTOWN UNIT 1 - SAMPLING POINTS (DUCT 1A)


2.13m
1.83m
1.52m
1.22m
0.91m
0.61m
0.30m
X_2
X_1
0.94m
1.97m
3.00m
4.04m
5.07m
6.09m
7.08m
8.06m
9.07m
10.09m
11.10m
12.12m
1.22m
10.15m

Nominal dimensions - Width - 12.50m
Depth - 2.45m

FIGURE 24

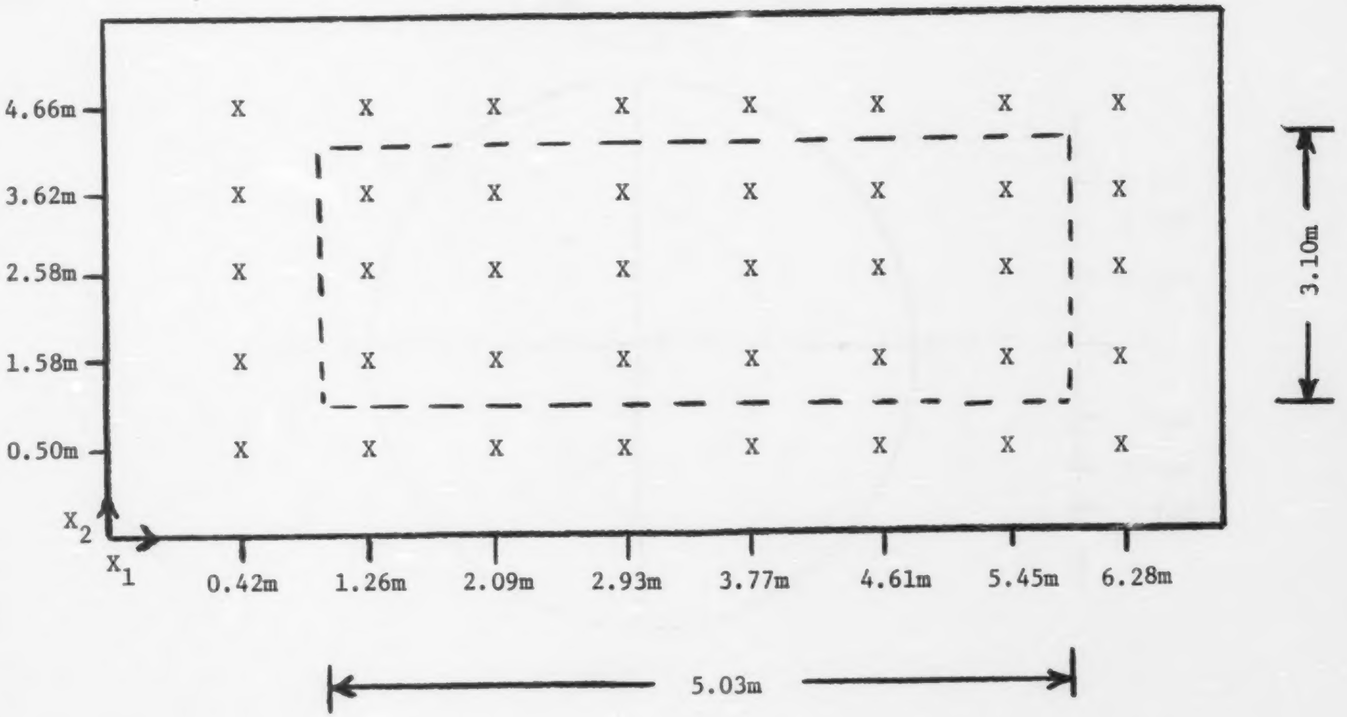
MORGANTOWN UNIT 1 - SAMPLING POINTS (DUCT 1B)


2.13m
1.83m
1.52m
1.22m
0.91m
0.61m
0.30m
X_2
X_1
0.43m
1.45m
2.49m
3.51m
4.52m
5.55m
6.52m
7.58m
8.63m
9.62m
10.63m
11.67m
10.21m
1.22m

Nominal dimensions - Width - 12.50m
Depth - 2.45m

FIGURE 25

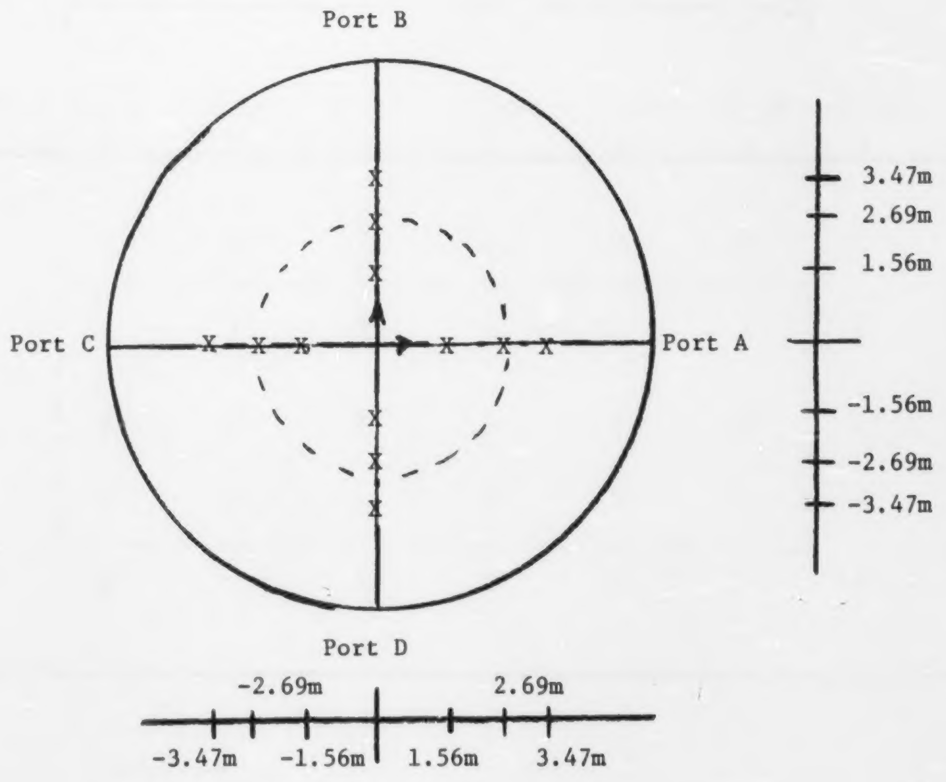
NAVAJO UNIT 1 - SAMPLING POINTS (DUCTS A,B,C, AND D)


4.66m
3.62m
2.58m
1.58m
0.50m
X_2
X_1
0.42m
1.26m
2.09m
2.93m
3.77m
4.61m
5.45m
6.28m
3.10m
5.03m

Nominal dimensions - Width - 7.01m
Depth - 5.18m

FIGURE 26

NAVAJO UNIT 1 - SAMPLING POINTS (STACK)


Port B
Port C
Port A
Port D
3.47m
2.69m
1.56m
-1.56m
-2.69m
-3.47m
-2.69m
2.69m
-3.47m
-1.56m
1.56m
3.47m

Nominal dimension - Diameter -7.62m

3.2.3 Testing Techniques

As the majority of modern power plant boilers split the flue gas stream into more than one duct, at least two ducts from each boiler were tested. Two-man test teams were assigned to each duct to position the probes and to record temperature and velocity readings. A fifth member of the team remained in the sampling/analytical van to record gas concentration data. The sampling was performed simultaneously from the two ducts. While one sample was monitored, the other was vented to assure that a fresh sample would be available when required. Sampling was done at each point for approximately 1 to 2 minutes. The response time from the probe tip to the analyzer readout was usually 30 seconds. The probe from which we were not analyzing was relocated in the duct at that time. This technique resulted in a substantial reduction in the length of each test. The length of each test usually lasted 3-5 hours. Also, duplicate measurements were obtained at each sampling point by repeating each traverse. The moisture content of the flue gas was measured using the wet/dry bulb method both at the start and end of each test.

4. FIELD MEASUREMENT RESULTS

4.1 Stratification Results for Individual Units Tested

In this section the detailed results obtained in testing individual units are presented. The gaseous concentrations, temperature, and velocity profiles determined were subjected to statistical analysis using linear, quadratic, and cubic regression models. These models are discussed in Section 4.2.1.

4.1.1 Widows Creek Unit 5 (TVA)

Tennessee Valley Authority's Unit 5 at the Widows Creek Steam Plant was the first boiler to be tested in our program. This unit is a 125 MW, 16 burner, front wall, pulverized coal fired Babcock and Wilcox boiler. It has a single dry bottom furnace with a division wall, and the 16 burners are arranged with four burners in each of four rows. Each row is fed with coal by a separate pulverizer.

Stratification testing was performed with the unit operating at 100 MW. Sampling was done downstream of the rotary air preheater just upstream of the induced draft fan. The sampling location is shown in Figure 8. Figures 15 and 16 show the dimensions and locations of the sampling points for ducts 5A and 5B, respectively. The dashed rectangles represent the area from which the inner duct averages were calculated. For duct 5A, this represents the inner 44.9% of the duct and for duct 5B, this represents the inner 47.6% of the duct. Table 19 shows the differences between the total duct averages and the inner duct averages for both ducts 5A and 5B. As shown, the differences are negligible. This means that a traverse of the inner portion of the duct can be used to obtain a representative duct average. Table 20 shows the differences between the standard deviations in the measurements for both the total duct and inner duct measurements. In most cases, the standard deviations decrease or increase insignificantly. Also, in most cases, the standard deviations are relatively small which indicates that the degree of dispersion in our measurements is relatively small. Table 21 shows that duct-to-duct stratification is negligible. Tables 22 and 23 show that of all the models tested, a quadratic model can best be used to express the gas component concentrations, velocity, and temperature as a function of position within the duct. Also, on a 3% O_2 basis, all correlations become negligible, which implies that the gas component concentrations become independent of position in the duct cross section.

4.1.2 Widows Creek Unit 7 (TVA)

Tennessee Valley Authority's Unit 7 at the Widows Creek Steam Plant was the second boiler to be tested in our program. This unit is a 575 MW, twin furnace, tangential, pulverized coal fired Combustion Engineering boiler. Each furnace has 20 burners (5 in each corner). Unit 7 is equipped with electrostatic precipitators downstream of the air heater and an ammonia injection system for flue gas conditioning. This unit went into commercial operation in 1961.

TABLE 19

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 5

	Duct 5A Duct Average	Inner 44.9% Ave.	% Difference	Duct 5B Duct Average	Inner 47.6% Ave.	% Difference
SO_2 (ppm)	1417	1414	-0.2	1397	1398	+0.1
NO (ppm)	564	563	-0.2	578	579	+0.2
CO_2 (%)	16.0	16.0	0.0	15.9	15.9	0.0
O_2 (%)	7.7	7.6	-1.3	8.7	8.7	0.0
Velocity (M/S)	9.6	9.1	-5.2	9.0	8.4	-6.7
Temperature (°C)	183	183	0.0	172	171	-0.6

TABLE 20

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 5

Standard Deviation* in Measurements

	Duct 5A			Duct 5B		
	Total Duct	Inner 44.9%	% Difference	Total Duct	Inner 47.6%	% Difference
SO_2 (ppm)	118	130	+9.70	144.57	151.59	+4.86
NO (ppm)	19	21	+8.41	16.70	15.47	-7.37
CO_2 (%)	0.4	0.3	-24.39	0.62	0.76	+22.58
O_2 (%)	0.9	0.7	-26.97	0.78	0.62	-20.51
Velocity (M/S)	2.0	2.0	-0.51	2.61	2.86	+9.58
Temperature (°C)	3	3	-16.95	4.00	2.89	-27.75

$$* \quad \sigma = \left(\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n-1} \right)^{1/2}$$

TABLE 21

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 5

Magnitude of the Duct-to-Duct Stratification

		Duct 5A		Duct 5B	
	Boiler Average	Average	% Difference	Average	% Difference
SO_2 (ppm)	1407	1417	+0.71	1397	-0.71
NO (ppm)	571	564	-1.23	578	+1.23
CO_2 (%)	15.95	16.0	+0.31	15.9	-0.31
O_2 (%)	8.2	7.7	-6.10	8.7	+6.10
Velocity (M/S)	9.3	9.6	+3.23	9.0	-3.23
Temperature (°C)	177.5	183	+3.10	172	-3.10

TABLE 22

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 5 (DUCT 5A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.31	0.11	0.32	0.13	--	--
NO (ppm)	0.83	0.02	0.86	0.12	--	--
CO_2 (%)	0.73	0.08	0.76	0.24	--	--
O_2 (%)	0.76	--	0.81	--	--	--
Velocity (M/S)	0.69	--	0.93	--	--	--
Temperature (°C)	0.50	--	0.54	--	--	--

TABLE 23

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 5 (DUCT 5B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.22	0.10	0.24	0.15	--	--
NO (ppm)	0.86	0.11	0.87	0.14	--	--
CO_2 (%)	0.71	0.00	0.72	0.02	--	--
O_2 (%)	0.88	--	0.91	--	--	--
Velocity (M/S)	0.71	--	0.90	--	--	--
Temperature (°C)	0.84	--	0.85	--	--	--

Stratification testing was performed with the unit operating at 400 MW. Sampling was done downstream of the rotary air preheater just upstream of the electrostatic fly-ash collector. The sampling location is shown in Figure 9. Figure 17 shows the dimensions and locations of the sampling points for ducts 7A and 7B. The dashed rectangle represents the area from which the inner duct averages were calculated. For both ducts 7A and 7B this represents the inner 49.8% of the duct. Table 24 shows the differences between the total duct averages and the inner duct averages for both ducts 7A and 7B. As shown, the differences are negligible. This means that a traverse of the inner portion of the duct can be used to obtain a representative duct average. Table 25 shows the differences between the standard deviations in the measurements for both the total duct and inner duct measurements. In most cases, the standard deviations decrease or increase insignificantly. Also, the degree of dispersion in our measurements is relatively small in most cases. Table 26 shows that duct-to-duct stratification is negligible. Tables 27 and 28 show that a cubic model can best be used to express the gas component concentrations, velocity, and temperature as a function of position within the duct. Also, on a 3% O_2 basis, all correlations are reduced significantly.

4.1.3 E.C. Gaston Unit 5 (Southern Electric Generating Company)

Southern Electric Generating Company's Unit 5 at the E.C. Gaston Steam Plant was the third boiler to be tested in our program. This unit is a 900 MW, twin furnace, tangential, pulverized coal fired Combustion Engineering boiler. Each furnace has 28 burners (7 in each corner).

Stratification testing was performed with the unit operating at 850 MW. Sampling was done just downstream of the air preheater (Figure 10). Figure 18 shows the dimensions and locations of the sampling points for ducts 5A and 5B. The dashed rectangle represents the area from which the inner duct averages were calculated. For both ducts 5A and 5B, this represents the inner 43.7% of the duct. Table 29 shows the differences between the total duct averages and the inner duct averages for both ducts 5A and 5B. As shown, the differences are negligible. This means that a traverse of the inner portion of the duct can be used to obtain a representative duct average. Table 30 shows the differences between the standard deviations in the measurements for both the total duct and inner duct measurements. In most cases, the standard deviations decrease or increase insignificantly. This table also indicates that in most cases the degree of dispersion in our data is relatively small. Table 31 shows that duct-to-duct stratification is negligible. Tables 32 and 33 show that a cubic model can best be used to express the gas component concentrations, velocity, and temperature as a function of position within the duct. Also, on a 3% O_2 basis, all correlations are significantly reduced.

4.1.4 Barry Unit 4 (Alabama Power Company)

Alabama Power Company's Unit 4 at their Barry Plant was the fourth boiler to be tested in our program. This unit is a 350 MW, tangential, pulverized coal fired Combustion Engineering boiler.

Stratification testing was performed with the unit operating at 240 MW. Sampling was done just downstream of the electrostatic precipitator. It should be noted that the precipitator was off when the testing

TABLE 24

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 7

	Duct 7A			Duct 7B		
	Duct Average	Inner 49.8% Ave.	% Difference	Duct Average	Inner 49.8% Ave.	% Difference
SO_2 (ppm)	2578	2545	-1.3	2426	2405	-0.9
NO (ppm)	341	340	-0.3	386	386	0.0
CO_2 (%)	14.4	14.4	0.0	14.5	14.8	+2.1
O_2 (%)	4.3	4.0	-7.0	4.8	4.4	-8.3
Velocity (M/S)	6.4	6.4	0.0	6.3	6.4	+1.6
Temperature (°C)	141	143	+1.4	134	139	+3.7

TABLE 25

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 7

Standard Deviation in Measurements

	Duct 7A			Duct 7B		
	Total Duct	Inner 49.8%	% Difference	Total Duct	Inner 49.8%	% Difference
SO_2 (ppm)	437.69	330.80	-24.42	325.35	290.50	-10.71
NO (ppm)	22.81	22.61	-0.88	20.10	16.87	-16.07
CO_2 (%)	0.78	0.85	+8.97	0.67	0.94	+40.30
O_2 (%)	0.75	0.52	-30.67	0.55	0.32	-41.82
Velocity (M/S)	2.25	1.66	-26.22	1.79	1.62	-9.50
Temperature (°C)	9.60	7.04	-26.67	12.78	8.55	-33.10

TABLE 26

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 7

Magnitude of the Duct-to-Duct Stratification

		Duct 7A		Duct 7B	
	Boiler Average	Average	% Difference	Average	% Difference
SO_2 (ppm)	2502	2578	+3.04	2426	-3.04
NO (ppm)	363.5	341	-6.19	386	+6.19
CO_2 (%)	14.45	14.4	-0.35	14.5	+0.35
O_2 (%)	4.55	4.3	-5.49	4.8	+5.49
Velocity (M/S)	6.35	6.4	+0.79	6.3	-0.79
Temperature (°C)	137.5	141	+2.55	134	-2.55

TABLE 27

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 7 (DUCT 7A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.01	0.02	0.02	0.03	0.03	0.04
NO (ppm)	0.06	0.14	0.21	0.21	0.24	0.23
CO_2 (%)	0.43	0.15	0.49	0.21	0.50	0.23
O_2 (%)	0.40	--	0.68	--	0.72	--
Velocity (M/S)	0.27	--	0.73	--	0.74	--
Temperature (°C)	0.65	--	0.78	--	0.82	--

TABLE 28

STRATIFICATION RESULTS - WIDOWS CREEK UNIT 7 (DUCT 7B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.01	0.02	0.06	0.06	0.12	0.07
NO (ppm)	0.05	0.12	0.29	0.32	0.40	0.32
CO_2 (%)	0.02	0.00	0.23	0.10	0.43	0.13
O_2 (%)	0.07	--	0.30	--	0.67	--
Velocity (M/S)	0.32	--	0.50	--	0.65	--
Temperature (°C)	0.27	--	0.77	--	0.80	--

TABLE 29

STRATIFICATION RESULTS - E.C. GASTON UNIT 5

	Duct 5A			Duct 5B		
	Duct Average	Inner 43.7% Ave.	% Difference	Duct Average	Inner 43.7% Ave.	% Difference
SO_2 (ppm)	1162	1211	+4.2	1190	1203	+1.1
NO (ppm)	605	614	+1.5	514	516	+0.4
CO_2 (%)	14.4	14.6	+1.4	14.7	14.8	+0.7
O_2 (%)	6.1	5.6	-8.2	5.6	5.0	-10.7
Velocity (M/S)	17.1	17.9	+4.7	13.2	14.0	+6.1
Temperature (°C)	141	144	+1.4	121	125	+3.3

TABLE 30

STRATIFICATION RESULTS - E.C. GASTON UNIT 5

Standard Deviation in Measurements

	Duct 5A			Duct 5B		
	Total Duct	Inner 43.7%	% Difference	Total Duct	Inner 43.7%	% Difference
SO_2 (ppm)	182.58	253.75	+38.98	86.14	92.94	+7.89
NO (ppm)	22.29	15.09	-32.30	12.43	10.97	-11.75
CO_2 (%)	0.58	0.58	0.00	0.53	0.28	-47.17
O_2 (%)	0.71	0.22	-69.01	0.81	0.26	-67.90
Velocity (M/S)	6.46	3.98	-38.39	4.76	2.77	-41.81
Temperature (°C)	13.35	6.78	-49.21	12.46	8.27	-33.63

TABLE 31

STRATIFICATION RESULTS - E.C. GASTON UNIT 5

Magnitude of the Duct-to-Duct Stratification

	Boiler Average	Duct 5A		Duct 5B	
		Average	% Difference	Average	% Difference
SO_2 (ppm)	1176	1162	-1.19	1190	+1.19
NO (ppm)	559.5	605	+8.13	514	-8.13
CO_2 (%)	14.55	14.4	-1.03	14.7	+1.03
O_2 (%)	5.85	6.1	+4.27	5.6	-4.27
Velocity (M/S)	15.15	17.1	+12.87	13.2	-12.87
Temperature (°C)	131.5	142	+7.98	121	-7.98

TABLE 32

STRATIFICATION RESULTS - E.C. GASTON UNIT 5 (DUCT 5A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	--	--	0.25	0.15	0.27	0.18
NO (ppm)	--	--	0.59	0.32	0.65	0.38
CO_2 (%)	--	--	0.67	0.46	0.74	0.52
O_2 (%)	--	--	0.55	--	0.66	--
Velocity (M/S)	--	--	0.72	--	0.77	--
Temperature (°C)	--	--	0.74	--	0.78	--

TABLE 33

STRATIFICATION RESULTS - E.C. GASTON UNIT 5 (DUCT 5B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	--	--	0.46	0.24	0.47	0.26
NO (ppm)	--	--	0.53	0.12	0.67	0.28
CO_2 (%)	--	--	0.63	0.34	0.69	0.41
O_2 (%)	--	--	0.60	--	0.74	--
Velocity (M/S)	--	--	0.72	--	0.74	--
Temperature (°C)	--	--	0.82	--	0.84	--

was performed. The sampling location is shown in Figure 11. Figures 19 and 20 show the dimensions and locations of the sampling points for ducts 4A and 4B, respectively. The nominal duct dimensions are 16 ft. wide by 14-1/2 ft. deep. The dashed rectangles represent the area from which the inner duct averages were calculated. For both ducts, this represents approximately the inner 32% of the duct. Table 34 shows the differences between the total duct averages and the inner duct averages for both ducts 4A and 4B. As shown, the differences are negligible. This means that a traverse of the inner portion of the duct can be made to determine a representative duct average. Table 35 shows the differences between the standard deviations in the measurements for both the total duct and inner duct measurements. In most cases, the standard deviations decrease or increase insignificantly. Also, in most cases the standard deviations are relatively small which indicates that the degree of dispersion in our measurements is small. Table 36 shows that duct-to-duct stratification is negligible. Tables 37 and 38 show that a cubic model can best be used to express the gas component concentrations, velocity, and temperature as a function of position within the duct. It is important to note that on a 3% O_2 basis the correlations are reduced.

4.1.5 Barry Unit 5 (Alabama Power Company)

Alabama Power Company's Unit 5 at their Barry Plant was the fifth boiler tested in our program. This unit is a 712 MW, twin furnace, tangential, pulverized coal fired Combustion Engineering boiler.

Stratification testing was performed with the unit operating at 450 MW. Sampling was done downstream of the air preheater just upstream of the electrostatic precipitator. Figure 12 shows the location of the sampling ports. Figures 21 and 22 show the dimensions and locations of the sampling points for ducts 5A and 5B, respectively. The nominal duct dimensions are 40 ft. wide by 9 ft. deep. The dashed rectangles represent the area from which the inner duct averages were calculated. For both ducts, this represents approximately the inner 43% of the duct. Table 39 shows the differences between the total duct averages and the inner duct averages for both ducts 5A and 5B. As shown, the differences are negligible. This means that a traverse of the inner portion of the duct can be used to obtain a representative duct average. Table 40 shows the differences between the standard deviations in the measurements for both the total duct and inner duct measurements. The magnitude of standard deviations indicates that the degree of dispersion in most cases is relatively small. Table 41 shows that duct-to-duct stratification is negligible. Tables 42 and 43 show that a cubic model can best be used to express the gas component concentrations, velocity, and the temperature as a function of position within the duct. Also, on a 3% O_2 basis all correlations are reduced.

TABLE 34

STRATIFICATION RESULTS - BARRY UNIT 4

	Duct 4A			Duct 4B		
	Duct Average	Inner 32.2% Ave.	% Difference	Duct Average	Inner 32.0% Ave.	% Difference
SO_2 (ppm)	1746	1751	+0.3	1742	1746	+0.2
NO (ppm)	359	354	-1.4	377	373	-1.1
CO_2 (%)	15.97	16.01	+0.3	15.85	15.83	-0.1
O_2 (%)	5.8	5.7	-1.7	6.1	5.9	-3.3
Velocity (M/S)	12.02	11.13	-7.4	11.47	10.61	-7.5
Temperature (°C)	159	160	+0.6	131	130	-0.8

TABLE 35

STRATIFICATION RESULTS - BARRY UNIT 4

Standard Deviation in Measurements

	Duct 4A Total Duct	Duct 4A Inner 32.2%	Duct 4A % Difference	Duct 4B Total Duct	Duct 4B Inner 32.0%	Duct 4B % Difference
SO_2 (ppm)	51.29	46.39	-9.6	54.47	42.91	-21.2
NO (ppm)	22.73	25.75	+13.3	19.76	18.51	-6.3
CO_2 (%)	0.50	0.58	+16.0	0.46	0.54	+17.4
O_2 (%)	0.61	0.66	+8.2	0.59	0.52	-11.9
Velocity (M/S)	1.51	1.02	-32.5	1.46	0.74	-49.3
Temperature (°C)	19.39	7.87	-59.4	6.99	5.81	-16.9

TABLE 36

STRATIFICATION RESULTS - BARRY UNIT 4

Magnitude of the Duct-to-Duct Stratification

	Boiler Average	Duct 4A		Duct 4B	
		Average	% Difference	Average	% Difference
SO_2 (ppm)	1744	1746	+0.1	1742	-0.1
NO (ppm)	368	359	-2.4	377	+2.4
CO_2 (%)	15.91	15.97	+0.4	15.85	-0.4
O_2 (%)	5.95	5.8	-2.5	6.1	+2.5
Velocity (M/S)	11.75	12.02	+2.3	11.47	-2.3
Temperature (°C)	145	159	+9.7	131	-9.7

TABLE 37

STRATIFICATION RESULTS - BARRY UNIT 4 (DUCT 4A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.43	0.12	0.52	0.19	0.58	0.25
NO (ppm)	0.19	0.02	0.35	0.14	0.39	0.18
CO_2 (%)	0.27	0.31	0.32	0.34	0.36	0.44
O_2 (%)	0.23	--	0.26	--	0.29	--
Velocity (M/S)	0.52	--	0.70	--	0.76	--
Temperature (°C)	0.69	--	0.72	--	0.79	--

TABLE 38

STRATIFICATION RESULTS - BARRY UNIT 4 (DUCT 4B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.15	0.23	0.52	0.26	0.58	0.35
NO (ppm)	0.19	0.06	0.38	0.20	0.48	0.23
CO_2 (%)	0.07	0.16	0.28	0.20	0.28	0.25
O_2 (%)	0.08	--	0.40	--	0.42	--
Velocity (M/S)	0.50	--	0.77	--	0.85	--
Temperature (°C)	0.73	--	0.75	--	0.79	--

TABLE 39

STRATIFICATION RESULTS - BARRY UNIT 5

	Duct 5A			Duct 5B		
	Duct Average	Inner 43.6% Ave.	% Difference	Duct Average	Inner 43.7% Ave.	% Difference
SO_2 (ppm)	2409	2446	+1.54	2312	2334	+0.95
NO (ppm)	371	374	+0.81	343	346	+0.87
CO_2 (%)	15.26	15.39	+0.85	14.25	14.50	+1.75
O_2 (%)	5.0	4.6	-8.00	7.8	7.4	-5.13
Velocity (M/S)	5.34	5.61	+5.06	4.68	4.96	+5.98
Temperature (°C)	119	121	+1.68	117	120	+2.56

TABLE 40

STRATIFICATION RESULTS - BARRY UNIT 5

Standard Deviation in Measurements

	Duct 5A Total Duct	Duct 5A Inner 43.6%	Duct 5A % Difference	Duct 5B Total Duct	Duct 5B Inner 43.7%	Duct 5B % Difference
SO_2 (ppm)	83.66	45.13	-46.06	138.34	79.62	-42.45
NO (ppm)	20.99	22.52	+7.29	13.65	8.34	-38.90
CO_2 (%)	0.54	0.40	-25.93	0.85	0.71	-16.47
O_2 (%)	0.60	0.87	+45.00	1.22	0.82	-32.79
Velocity (M/S)	1.01	0.77	-23.76	0.92	0.76	-17.39
Temperature (°C)	7.56	5.97	-21.03	11.23	9.91	-11.75

TABLE 41

STRATIFICATION RESULTS - BARRY UNIT 5

Magnitude of the Duct-to-Duct Stratification

	Boiler Average	Duct 5A		Duct 5B	
		Average	% Difference	Average	% Difference
SO_2 (ppm)	2361	2409	+2.03	2312	-2.03
NO (ppm)	357	371	+3.92	343	-3.92
CO_2 (%)	14.76	15.26	+3.39	14.25	-3.39
O_2 (%)	6.4	5.0	-21.88	7.8	+21.88
Velocity (M/S)	5.01	5.34	+6.59	4.68	-6.59
Temperature (°C)	118	119	+0.85	117	-0.85

TABLE 42

STRATIFICATION RESULTS - BARRY UNIT 5 (DUCT 5A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.11	0.04	0.71	0.21	0.78	0.26
NO (ppm)	0.11	0.03	0.52	0.12	0.53	0.13
CO_2 (%)	0.06	0.02	0.71	0.17	0.79	0.19
O_2 (%)	0.18	--	0.78	--	0.86	--
Velocity (M/S)	0.24	--	0.30	--	0.32	--
Temperature (°C)	0.89	--	0.95	--	0.96	--

TABLE 43

STRATIFICATION RESULTS - BARRY UNIT 5 (DUCT 5B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.30	0.24	0.61	0.34	0.70	0.56
NO (ppm)	0.32	0.27	0.70	0.36	0.77	0.57
CO_2 (%)	0.29	0.29	0.65	0.51	0.67	0.54
O_2 (%)	0.25	--	0.64	--	0.67	--
Velocity (M/S)	0.16	--	0.27	--	0.29	--
Temperature (°C)	0.49	--	0.64	--	0.68	--

4.1.6 Morgantown Unit 1 (Potomac Electric Power Company)

Potomac Electric Power Company's Unit 1 at their Morgantown Plant was the sixth boiler to be tested in our program. This unit is a 575 MW, mixed fuel, Combustion Engineering boiler.

Stratification testing was performed with the unit operating at full load, firing 75% oil and 25% coal. Sampling was done just upstream of the electrostatic precipitator (Figure 13). Figures 23 and 24 shows the dimensions and locations of the sampling points for ducts 1A and 1B, respectively. The nominal duct dimensions are 41 ft. wide by 8 ft. deep. The dashed rectangles represent the area from which the inner duct averages were calculated. For both ducts this represents approximately the inner 40% of the cross sectional area. Table 44 shows that the differences between the total and inner duct averages are negligible. Table 46 shows that the duct-to-duct stratification is negligible. Tables 47 and 48 indicate that a cubic model can best be used to express the gas component concentrations, velocity, and temperatures as a function of position within the duct. Once again, it is important to note that on a 3% O_2 basis all correlations are reduced significantly.

4.1.7 Navajo Unit 1 (Salt River Project)

Unit 1 at the Navajo Generating Station was the seventh boiler tested in our program. This unit is an 800 MW, twin furnace, tangentially fired, Combustion Engineering boiler.

Stratification testing was performed with the unit operating at 800 MW. Sampling was done downstream of the rotary air preheater just upstream of the induced draft fan. The sampling location is shown in Figure 14. Figure 25 shows the dimensions and locations of the sampling points for ducts 1A, 1B, 1C, and 1D. The dashed rectangles show the area from which the inner duct averages were calculated. This represents the inner 43% of the duct cross sectional area. Table 49 shows the differences between the total duct averages and the inner duct averages for all four ducts. As shown, the differences are negligible. This means that a traverse of the inner portion of the duct can be used to obtain a representative duct average. Table 50 shows that the standard deviations are relatively small which indicates that the degree of dispersion in our measurements is relatively small. Table 51 shows that there is no significant difference between the individual duct averages and the boiler averages. This means that duct-to-duct stratification is negligible. Tables 52, 53, 54, and 55 show that of all the models tested a cubic model can best be used to express the gas component concentrations, velocity, and temperature as a function of position within the duct. Also, on a 3% O_2 basis, all correlations become negligible.

On this unit, stratification tests were also performed 350 feet up in the stack. Tests were conducted at both 725 and 800 MW. The positions of the sampling points are shown in Figure 26. The test results are shown in Tables 56-58. As can be seen, there is no appreciable difference between the total and inner duct averages.

TABLE 44

STRATIFICATION RESULTS - MORGANTOWN UNIT 1

	Duct 1A			Duct 1B		
	Duct Average	Inner 40.6% Ave.	% Difference	Duct Average	Inner 40.9% Ave.	% Difference
SO_2 (ppm)	1353	1358	+0.4	1261	1262	+0.1
NO (ppm)	374	369	-1.3	419	420	+0.2
CO_2 (%)	14.2	14.3	+0.7	14.1	14.1	0.0
O_2 (%)	5.2	4.7	-9.6	5.4	5.1	-5.6
Velocity (M/S)	13.8	13.6	-1.4	14.7	14.5	-1.4
Temperature (°C)	143	143	0.0	138	137	-0.7

TABLE 45

STRATIFICATION RESULTS - MORGANTOWN UNIT 1

Standard Deviation in Measurements

	Duct 1A			Duct 1B		
	Total Duct	Inner 40.6%	% Difference	Total Duct	Inner 40.9%	% Difference
SO_2 (ppm)	53.37	51.72	-3.1	43.92	40.37	-8.1
NO (ppm)	31.28	32.66	+4.4	35.05	27.80	-20.7
CO_2 (%)	0.49	0.39	-20.4	0.40	0.35	-12.5
O_2 (%)	1.10	0.44	-60.0	0.93	0.70	-24.7
Velocity (M/S)	4.51	3.70	-18.0	4.91	3.98	-18.9
Temperature (°C)	10.92	8.45	-22.6	9.43	8.31	-11.9

TABLE 46

STRATIFICATION RESULTS - MORGANTOWN UNIT 1

Magnitude of the Duct-to-Duct Stratification

		Duct 1A		Duct 1B	
	Boiler Average	Average	% Difference	Average	% Difference
SO_2 (ppm)	1307	1353	+3.5	1261	-3.5
NO (ppm)	397	374	-5.8	419	+5.8
CO_2 (%)	14.15	14.2	+0.4	14.1	-0.4
O_2 (%)	5.15	5.2	+1.0	5.1	-1.0
Velocity (M/S)	14.2	13.8	-2.8	14.5	+2.8
Temperature (°C)	140	143	+2.1	137	-2.1

TABLE 47

STRATIFICATION RESULTS - MORGANTOWN UNIT 1 (Duct 1A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.25	0.06	0.61	0.07	0.68	0.07
NO (ppm)	0.25	0.12	0.35	0.14	0.42	0.18
CO_2 (%)	0.42	0.23	0.76	0.35	0.81	0.37
O_2 (%)	0.38	--	0.76	--	0.83	--
Velocity (M/S)	0.52	--	0.67	--	0.72	--
Temperature (°C)	0.88	--	0.95	--	0.95	--

TABLE 48

STRATIFICATION RESULTS - MORGANTOWN UNIT 1 (Duct 1B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.26	0.03	0.41	0.11	0.43	0.19
NO (ppm)	0.32	0.32	0.41	0.34	0.44	0.39
CO_2 (%)	0.29	0.08	0.44	0.15	0.45	0.16
O_2 (%)	0.33	--	0.49	--	0.50	--
Velocity (M/S)	0.37	--	0.47	--	0.51	--
Temperature (°C)	0.68	--	0.72	--	0.80	--

TABLE 49

STRATIFICATION RESULTS - NAVAJO UNIT 1

	Duct 1A			Duct 1B			Duct 1C			Duct 1D		
	Duct Average	Inner 43% Ave.	% Difference	Duct Average	Inner 43% Ave.	% Difference	Duct Average	Inner 43% Ave.	% Difference	Duct Average	Inner 43% Ave.	% Difference
SO_2 (ppm)	438	433	-1.1	507	525	3.6	435	446	2.5	463	493	6.5
NO (ppm)	310	313	1.0	310	308	-0.6	333	331	-0.6	335	331	-1.2
CO_2 (%)	15.7	15.7	0.0	15.5	15.5	0.0	15.5	15.6	0.6	15.3	15.2	-0.7
O_2 (%)	5.7	5.6	-1.8	6.9	6.8	-1.4	6.5	6.4	-1.5	6.9	6.9	0.0
Velocity (M/S)	10.2	10.1	-1.0	9.5	9.1	-4.2	9.4	9.2	-2.1	8.9	8.4	-5.6
Temperature (°C)	145	146	0.7	129	132	2.3	130	133	2.3	154	156	1.3

TABLE 50

STRATIFICATION RESULTS - NAVAJO UNIT 1

Standard Deviation in Measurements

	Duct 1A			Duct 1B			Duct 1C			Duct 1D		
	Total Duct	Inner 43%	% Difference	Total Duct	Inner 43%	% Difference	Total Duct	Inner 43%	% Difference	Total Duct	Inner 43%	% Difference
SO_2 (ppm)	35	21	-40.0	44	24	-45.5	40	25	-37.5	72	18	-75.0
NO (ppm)	11	8	-27.3	9	8	-11.1	8	7	-12.5	10	6	-40.0
CO_2 (%)	0.2	0.1	-50.0	0.2	0.1	-50.0	0.3	0.1	-66.7	0.2	0.2	0.0
O_2 (%)	0.2	0.1	-50.0	0.1	0.1	0.0	0.2	0.1	-50.0	0.2	0.1	-50.0
Velocity (M/S)	1.3	0.9	-30.8	1.4	0.9	-35.7	1.1	0.8	-27.3	1.9	1.5	-21.1
Temperature (°C)	12	12	0.0	8	1	-87.5	10	5	-50.0	4	2	-50.0

TABLE 51

STRATIFICATION RESULTS - NAVAJO UNIT 1

Magnitude of the Duct-to-Duct Stratification

	Boiler	Duct 1A		Duct 1B		Duct 1C		Duct 1D	
	Average	Average	% Difference	Average	% Difference	Average	% Difference	Average	% Difference
SO_2 (ppm)	461	438	-5.0	507	10.0	435	-5.6	463	-0.4
NO (ppm)	322	310	-3.7	310	-3.7	333	3.4	335	4.0
CO_2 (%)	15.5	15.7	1.3	15.5	0.0	15.5	0.0	15.3	-1.3
O_2 (%)	6.5	5.7	-12.3	6.9	6.2	6.5	0.0	6.9	6.2
Velocity (M/S)	9.5	10.2	7.4	9.5	0.0	9.4	-1.1	8.9	-6.3
Temperature (°C)	140	145	3.6	129	-7.9	130	-7.1	154	10.0

TABLE 52

STRATIFICATION RESULTS - NAVAJO UNIT 1 (DUCT 1A)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.29	0.32	0.38	0.43	0.48	0.50
NO (ppm)	0.55	0.41	0.62	0.56	0.63	0.60
CO_2 (%)	0.05	0.05	0.42	0.12	0.58	0.37
O_2 (%)	0.12	--	0.57	--	0.69	--
Velocity (M/S)	0.71	--	0.87	--	0.90	--
Temperature (°C)	0.25	--	0.41	--	0.76	--

TABLE 53

STRATIFICATION RESULTS - NAVAJO UNIT 1 (DUCT 1B)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.24	0.24	0.57	0.54	0.65	0.63
NO (ppm)	0.42	0.42	0.54	0.56	0.59	0.60
CO_2 (%)	0.32	0.31	0.55	0.35	0.63	0.43
O_2 (%)	0.02	--	0.40	--	0.42	--
Velocity (M/S)	0.04	--	0.51	--	0.83	--
Temperature (°C)	0.13	--	0.25	--	0.42	--

TABLE 54

STRATIFICATION RESULTS - NAVAJO UNIT 1 (DUCT 1C)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.06	0.08	0.30	0.26	0.39	0.36
NO (ppm)	0.09	0.13	0.34	0.30	0.39	0.38
CO_2 (%)	0.14	0.26	0.59	0.43	0.61	0.46
O_2 (%)	0.05	--	0.76	--	0.79	--
Velocity (M/S)	0.16	--	0.68	--	0.87	--
Temperature (°C)	0.24	--	0.68	--	0.80	--

TABLE 55

STRATIFICATION RESULTS - NAVAJO UNIT 1 (DUCT 1D)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.12	0.11	0.64	0.62	0.81	0.80
NO (ppm)	0.02	0.18	0.20	0.45	0.55	0.57
CO_2 (%)	0.45	0.13	0.48	0.55	0.71	0.66
O_2 (%)	0.37	--	0.66	--	0.81	--
Velocity (M/S)	0.58	--	0.72	--	0.87	--
Temperature (°C)	0.21	--	0.66	--	0.76	--

TABLE 56

STRATIFICATION RESULTS - NAVAJO UNIT 1 (IN STACK TEST)

	725 MW				800 MW			
	Average		Standard Deviation		Average		Standard Deviation	
	Total	Inner	Total	Inner	Total	Inner	Total	Inner
SO_2 (ppm)	553	549	25	27	554	551	16	14
NO (ppm)	294	295	18	21	299	299	15	14
CO_2 (%)	14.6	14.6	0.8	0.8	15.5	15.5	0.3	0.2
O_2 (%)	6.2	6.2	0.2	0.2	6.2	6.3	0.2	0.3
Velocity (M/S)	31.5	33.0	2.2	0.7	41.5	43.9	4.1	2.2
Temperature (°C)	139	139	2	2	149	149	1	1

TABLE 57

STRATIFICATION RESULTS - NAVAJO UNIT 1 (IN STACK AT 725 MW)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.12	0.23	0.19	0.33	0.28	0.36
NO (ppm)	0.29	0.32	0.46	0.52	0.62	0.61
CO_2 (%)	0.03	0.04	0.18	0.19	0.26	0.29
O_2 (%)	0.04	--	0.04	--	0.34	--
Velocity (M/S)	0.39	--	0.71	--	0.82	--
Temperature (°C)	0.02	--	0.08	--	0.10	--

TABLE 58

STRATIFICATION RESULTS - NAVAJO UNIT 1 (IN STACK AT 800 MW)

Fraction of Explained Variance

	Linear Model		Quadratic Model		Cubic Model	
	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis	As Measured	3% O_2 Basis
SO_2 (ppm)	0.07	0.03	0.26	0.17	0.27	0.22
NO (ppm)	0.07	0.05	0.20	0.14	0.27	0.22
CO_2 (%)	0.04	0.11	0.11	0.16	0.24	0.30
O_2 (%)	0.02	--	0.04	--	0.33	--
Velocity (M/S)	0.19	--	0.64	--	0.76	--
Temperature (°C)	0.02	--	0.03	--	0.04	--

4.2 Development of Contour Diagrams

To present the gaseous concentration, temperature, and velocity profiles measured in the ducts and stacks tested, multiple regression analyses were done to provide models for developing contour diagrams. This section presents the details of the analytical techniques used and contour diagrams produced based on this approach.

4.2.1 Multiple Regression Analysis

A computer program which utilized Exxon's IBM 1130 computer was used to facilitate the handling of data obtained from our stratification program. This program is divided into three subprograms:

1. Data reduction program
2. Multiple regression analysis program
3. Contour plotting program

The data reduction program is a modification of the data reduction program used in Exxon's basic study of NO_x formation in flames (Program VSEDR, developed under EPA Contract No. 68-02-0224). This program took the raw data and converted the concentration of the gaseous species to ppm (O_2 and CO_2 are converted to percent) and calculated the gas velocity at the various sampling points. The units of all measured quantities are metric units (SI). The data were then printed out in two tables. For each unit tested one table presents "as measured" values and the other table presents the values corrected to a three percent O_2 basis. A set of data tables for all of the units tested can be obtained from the EPA Project Officer.

The multiple regression program made it possible to develop an unlimited series of regression equations from a single deck of input data. This one deck could have contained as many as 675 observations on 45 variables. The computer first developed a complete correlation matrix from the data deck. By means of control cards the computer was then told which variables were to be considered dependent variables. This information enabled the computer to develop a sub-matrix from the complete correlation matrix. The sub-matrix was then used to calculate the first regression equation using either a direct or stepwise procedure. Additional cards then specified a new group of variables together with the dependent variables required for the second equation, and so on. In this manner, the user of the program was able to specify any desired combination of variables. To summarize, this program developed equations of the form:

$$y = f_i(x_1, x_2, \ldots, x_N)$$

where: y = dependent variable

f_i = polynomial of order i

X_i = independent variables

For the stratification study, the multiple regression analysis program used the results of the data reduction program to calculate regression equations giving the gas species concentration, flue gas velocity, and flue gas temperature as a function of position in the duct. For this study, the following models were used:

1. Linear model

$$y = b_o + b_1x_1 + b_2x_2$$

2. Quadratic model

$$y = b_o + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1x_2$$

3. Cubic model

$$y = b_o + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1x_2 + b_6x_1^3 + b_7x_2^2 + b_8x_1^2x_2 + b_9x_1x_2^2$$

Tables 59-61 present the regression equation coefficients for the three models.

The contour plotting program then used these equations to print contours of constant y.

Table 59

Linear Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2$$

	b_0	b_1	b_2
Widows Creek Unit 5 (Duct A)			
SO_2	1218.60	-40.47	-54.07
NO	473.37	-3.87	-26.30
CO_2	13.32	-0.08	-0.73
O_2	5.80	0.18	0.86
Temperature	188.61	0.12	-2.81
Velocity	8.30	1.51	-0.71
Widows Creek Unit 5 (Duct B)			
SO_2	1083.20	-15.69	-55.81
NO	435.77	2.64	-24.36
CO_2	11.89	0.16	-0.72
O_2	7.49	-0.18	0.82
Temperature	178.51	0.64	-4.20
Velocity	13.94	-2.02	-0.90
Widows Creek Unit 7 (Duct A)			
SO_2	2401.20	5.29	-32.68
NO	319.60	0.92	-4.52
CO_2	14.96	-0.19	-0.50
O_2	3.15	0.11	0.44
Temperature	150.35	-3.15	2.39
Velocity	4.67	-0.06	1.27
Widows Creek Unit 5 (Duct A)			
SO_2	2137.40	1.28	28.18
NO	351.23	0.23	-4.51
CO_2	13.26	-0.01	--
O_2	4.69	0.02	-0.02
Temperature	128.53	-0.60	5.86
Velocity	4.56	-0.01	1.11

E. C. Gaston Unit 5 - Linear Model Not Used

Table 59 (Continued)

Linear Regression Equation Coefficients

$$y = b_0 + b_1 x_1 + b_2 x_2$$

	b_0	b_1	b_2
Barry Unit 4 (Duct A)			
SO_2	1373.90	29.05	19.50
NO	286.92	1.20	4.40
CO_2	12.39	0.35	0.19
O_2	6.51	-0.17	-0.18
Temperature	142.06	5.02	3.43
Velocity	14.50	-0.35	-0.80
Barry Unit 4 (Duct B)			
SO_2	1374.80	15.95	12.53
NO	309.51	-3.87	2.88
CO_2	12.56	0.10	0.14
O_2	6.36	0.03	-0.13
Temperature	132.12	-3.76	3.27
Velocity	13.03	0.11	-0.80
Barry Unit 5 (Duct A)			
SO_2	2082.40	12.83	-15.97
NO	309.56	2.75	0.89
CO_2	13.16	0.06	0.02
O_2	5.63	-0.10	-0.01
Temperature	134.21	-2.07	-1.06
Velocity	5.63	-0.12	0.35
Barry Unit 5 (Duct B)			
SO_2	1900.60	-35.01	4.94
NO	274.87	-4.58	0.43
CO_2	11.80	-0.23	0.03
O_2	6.85	0.18	-0.06
Temperature	104.87	2.30	-1.17
Velocity	3.93	0.11	0.08

Table 59 (Continued)

Linear Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2$$

	b_0	b_1	b_2
Morgantown Unit 1 (Duct A)			
SO_2	1165.10	-6.88	52.53
NO	297.10	-0.83	24.22
CO_2	12.64	-0.16	0.67
O_2	5.22	0.14	-0.71
Temperature	155.50	-2.74	5.20
Velocity	22.03	-0.78	-2.54
Morgantown Unit 1 (Duct B)			
SO_2	1022.80	0.58	55.06
NO	303.39	4.52	21.61
CO_2	11.49	-0.03	0.70
O_2	6.25	0.01	-0.77
Temperature	145.92	-2.04	4.07
Velocity	13.47	0.69	-2.44
Navajo Unit 1 (Duct A)			
SO_2	392.99	-7.64	2.51
NO	253.68	3.41	0.01
CO_2	13.34	0.02	0.01
O_2	5.70	-0.03	0.02
Temperature	152.33	0.78	-3.82
Velocity	12.73	-0.49	-0.35
Navajo Unit 1 (Duct B)			
SO_2	440.69	-6.33	-8.17
NO	232.55	1.64	2.17
CO_2	12.36	-0.03	-0.04
O_2	6.84	0.01	0.01
Temperature	122.95	0.78	1.58
Velocity	9.96	0.00	-0.18
Navajo Unit 1 (Duct C)			
SO_2	362.92	-4.17	0.96
NO	272.97	-0.81	-0.71
CO_2	12.76	-0.05	-0.05
O_2	6.51	-0.01	0.01
Temperature	137.89	0.09	-3.18
Velocity	10.10	0.01	-0.29

Table 59 (Continued)

Linear Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2$$

	b_0	b_1	b_2
Navajo Unit 1 (Duct D)			
SO_2	391.48	1.87	-13.71
NO	259.34	0.33	0.48
CO_2	12.29	-0.06	-0.04
O_2	6.65	0.04	0.06
Temperature	155.64	0.44	-1.17
Velocity	7.12	0.71	-0.23
Navajo Unit 1 (Stack at 725 MW)			
SO_2	452.05	-1.07	4.67
NO	247.76	-3.78	-3.39
CO_2	11.66	-0.10	0.10
O_2	6.17	-0.01	0.02
Temperature	139.50	-0.07	-0.10
Velocity	3.24	-0.67	-0.52
Navajo Unit 1 (Stack at 800 MW)			
SO_2	454.29	-0.21	1.78
NO	244.64	0.42	1.63
CO_2	12.76	-0.02	-0.03
O_2	6.22	0.01	-0.01
Temperature	149.03	0.07	0.03
Velocity	4.23	-0.38	-0.92

Table 60

Quadratic Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2$$

	b_0	b_1	b_2	b_3	b_4	b_5
Widows Creek Unit 5 (Duct A)						
SO_2	1222.10	-101.23	-12.98	19.17	-9.84	-3.01
NO	469.55	-16.59	-12.48	4.54	-3.03	-1.62
CO_2	12.92	-0.34	-0.05	0.11	-0.16	-0.06
O_2	6.67	0.02	-0.01	-0.06	0.14	0.20
Temperature	186.43	3.56	-2.89	-0.84	0.16	-0.30
Velocity	14.10	-1.36	-5.58	0.40	0.96	0.81
Widows Creek Unit 5 (Duct B)						
SO_2	1110.90	-79.48	-47.85	19.11	-2.56	0.76
NO	436.03	6.32	-25.31	-2.02	-0.48	1.61
CO_2	11.65	0.35	-0.48	-0.08	-0.08	0.03
O_2	7.65	-0.58	0.84	0.14	0.01	-0.03
Temperature	178.82	1.54	-5.39	-0.24	0.36	-0.07
Velocity	17.06	-4.33	-4.39	1.01	1.22	-0.55
Widows Creek Unit 7 (Duct A)						
SO_2	2397.90	66.08	-153.11	-8.91	27.23	8.18
NO	309.95	5.12	9.29	-0.84	-6.59	1.74
CO_2	13.94	0.27	0.04	-0.05	-0.12	-0.04
O_2	4.04	-0.49	0.22	0.08	0.11	-0.03
Temperature	138.81	-1.23	17.97	-0.19	-4.61	-0.22
Velocity	5.60	-2.33	4.53	0.28	-0.96	0.05
Widows Creek Unit 7 (Duct B)						
SO_2	2240.80	-40.00	115.85	0.29	-38.33	7.09
NO	338.98	-0.46	17.13	-0.07	-9.50	2.18
CO_2	13.58	-0.22	0.73	0.0003	-0.32	0.06
O_2	4.47	0.17	-0.50	0.001	0.26	-0.08
Temperature	131.04	-4.33	27.78	0.04	-7.35	0.20
Velocity	2.46	0.05	4.79	0.002	-1.07	-0.07
E. C. Gaston Unit 5 (Duct A)						
SO_2	587.87	77.70	287.72	-4.10	-9.34	-9.34
NO	421.59	21.46	70.95	-1.45	-1.44	-1.44
CO_2	9.47	0.54	1.89	-0.03	-0.02	-0.02
O_2	8.34	-0.41	-2.38	0.02	0.04	0.04
Temperature	148.68	0.80	8.59	-0.24	-0.24	-0.24
Velocity	16.37	1.84	-4.93	-0.03	-0.86	-0.86

Table 60 (Continued)

Quadratic Regression Equation Coefficients

$$y = b_1 + b_1 x + b_2 x_2 + b_3 x_1^2 + b_4 x_2^2 + b_5 x_1 x_2$$

	b_0	b_1	b_2	b_3	b_4	b_5
E. C. Gaston Unit 5 (Duct B)						
SO_2	746.44	64.98	184.22	-3.50	-55.36	-7.71
NO	362.57	16.73	80.73	-0.95	-30.92	-1.69
CO_2	9.95	0.59	2.48	-0.03	-0.98	-0.05
O_2	7.93	-0.52	-2.43	0.03	0.92	-0.05
Temperature	93.40	5.47	12.13	-0.21	-4.94	-0.06
Velocity	11.14	2.49	-6.32	-0.12	2.10	-0.46
Barry Unit 4 (Duct A)						
SO_2	1319.10	106.71	17.07	-18.56	0.98	-0.94
NO	306.12	-17.53	1.80	3.06	-0.70	2.83
CO_2	12.03	0.83	0.18	-0.16	-0.01	0.03
O_2	6.79	-0.54	-0.22	0.10	0.02	-0.02
Temperature	141.65	3.58	6.35	0.05	-0.91	0.55
Velocity	16.98	-2.25	-2.26	0.46	0.32	0.02
Barry Unit 4 (Duct B)						
SO_2	1229.20	182.40	11.16	-33.84	4.51	-8.44
NO	308.63	10.18	-6.77	-4.34	1.08	2.21
CO_2	11.48	1.60	-0.09	-0.33	0.07	-0.03
O_2	7.60	-1.44	-0.09	0.31	-0.03	0.05
Temperature	130.53	-5.27	6.17	0.57	-0.44	-0.44
Velocity	15.90	-2.91	-1.42	0.70	0.15	-0.01
Barry Unit 5 (Duct A)						
SO_2	1709.90	144.82	135.91	-10.11	-44.99	-4.58
NO	250.87	26.08	10.83	-1.76	-1.16	-1.09
CO_2	9.76	-3.56	-1.81	0.13	-0.09	0.11
O_2	7.53	-0.88	-0.21	0.06	-0.01	0.03
Temperature	128.95	-0.77	5.02	-0.12	-2.60	0.17
Velocity	5.10	0.17	0.13	-0.02	0.07	0.01
Barry Unit 5 (Duct B)						
SO_2	1606.30	104.79	22.75	-11.82	-12.38	2.66
NO	231.45	16.23	-1.39	-1.69	1.22	-0.25
CO_2	9.45	0.85	0.19	-0.09	-0.03	-0.01
O_2	8.89	-0.78	0.02	0.08	-0.08	0.02
Temperature	89.91	5.22	17.96	-0.24	-7.03	0.02
Velocity	3.28	0.48	-0.22	-0.03	0.10	0.002

Table 60 (Continued)

Quadratic Regression Equation Coefficients

$$y = b_1 + b_1x + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1x_2$$

	b_0	b_1	b_2	b_3	b_4	b_5
Morgantown Unit 1 (Duct A)						
SO_2	1043.30	26.85	204.73	-3.38	-85.27	8.51
NO	271.50	6.49	53.83	-0.71	-16.43	1.59
CO_2	10.95	0.30	2.66	-0.04	-1.05	0.09
O_2	6.77	-0.32	-2.47	0.05	1.01	-0.11
Temperature	167.38	-5.71	-0.90	0.13	-0.20	1.01
Velocity	25.98	-2.75	-1.36	0.16	-0.32	-0.06
Morgantown Unit 1 (Duct B)						
SO_2	956.21	24.41	116.15	-2.25	-31.88	2.75
NO	308.85	8.60	9.64	-0.70	-3.98	3.58
CO_2	11.46	0.08	0.84	-0.02	-0.31	0.10
O_2	6.59	-0.18	-1.20	0.02	0.40	0.09
Temperature	152.84	-4.32	1.36	0.14	-0.16	0.51
Velocity	17.01	-1.17	-0.85	0.13	-1.14	0.20
Navajo Unit 1 (Duct A)						
SO_2	409.76	-25.33	6.99	2.53	-1.05	0.28
NO	243.81	5.40	7.07	-0.10	-1.04	-0.51
CO_2	13.57	-0.01	-0.09	-0.01	-0.01	-0.04
O_2	5.58	-0.04	0.06	0.01	0.01	-0.03
Temperature	144.49	-2.79	7.58	0.79	-1.78	0.66
Velocity	11.57	0.06	-0.27	-0.02	0.10	-0.17
Navajo Unit 1 (Duct B)						
SO_2	404.71	-6.58	39.38	-0.69	-10.43	1.88
NO	240.77	1.15	-5.03	-0.11	1.08	0.48
CO_2	12.25	0.08	-0.03	-0.02	-0.01	0.01
O_2	6.96	-0.07	-0.05	0.01	0.02	-0.01
Temperature	113.49	4.26	7.65	-0.49	-1.12	-0.08
Velocity	9.71	0.80	-1.54	-0.04	0.39	-0.20
Navajo Unit 1 (Duct C)						
SO_2	310.81	-1.92	49.44	0.65	-7.74	-2.54
NO	265.51	-2.24	7.90	0.42	-1.31	-0.54
CO_2	12.22	-0.04	0.54	0.00	-0.11	-0.004
O_2	6.96	-0.11	-0.36	0.01	0.07	0.004
Temperature	126.44	-2.53	13.83	0.33	-3.40	0.17
Velocity	12.29	0.06	-2.21	-0.08	0.24	0.20
Navajo Unit 1 (Duct D)						
SO_2	296.53	-5.63	104.66	1.09	-22.95	0.05
NO	259.17	-0.03	-1.15	0.33	0.77	-0.71
CO_2	12.42	-0.09	-0.13	0.003	0.02	0.003
O_2	6.89	0.07	-0.24	-0.006	0.06	0.003
Temperature	144.54	2.76	7.17	-0.19	-1.35	-0.42
Velocity	10.06	-0.06	-2.05	0.05	0.24	0.17

Table 60 (Continued)

Quadratic Regression Equation Coefficients

$$y = b_1+b_1x +b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2$$

	b_0	b_1	b_2	b_3	b_4	b_5
Navajo Unit 1 (Stack at 725 MW)						
SO_2	444.69	-1.35	0.91	0.76	2.30	0.00
NO	240.16	-4.14	-7.11	0.82	2.30	0.00
CO_2	12.57	0.12	0.13	-0.19	-0.11	0.00
O_2	6.17	-0.01	0.02	0.001	0.001	0.00
Temperature	139.00	-0.12	-0.29	0.06	0.13	0.00
Velocity	34.56	-0.27	-0.17	-0.38	-0.37	0.00
Navajo Unit 1 (Stack at 800 MW)						
SO_2	443.75	-2.25	0.54	1.93	1.51	0.00
NO	245.92	-0.54	2.98	0.39	-0.81	0.00
CO_2	12.65	-0.05	-0.03	0.03	0.01	0.00
O_2	6.26	0.02	-0.01	-0.01	-0.003	0.00
Temperature	149.20	0.09	0.06	-0.02	-0.03	0.00
Velocity	46.81	-0.005	0.14	-0.58	-0.93	0.00

Table 61

Cubic Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2+b_6x_1^3+b_7x_2^3+b_8x_1^2x_2+b_9x_1x_2^2$$

	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
Widows Creek Unit 5 (Duct A)	Cubic Model Not Used									
SO_2										
NO										
CO_2										
O_2										
Temperature										
Velocity										
Widows Creek Unit 5 (Duct B)	Cubic Model Not Used									
SO_2										
NO										
CO_2										
O_2										
Temperature										
Velocity										
Widows Creek Unit 7 (Duct A)										
SO_2	2241.40	170.65	51.18	-37.08	-50.92	-25.70	2.57	1.93	-2.32	16.69
NO	319.86	-5.38	-3.73	2.60	8.50	-0.63	-0.26	-0.40	-0.08	0.95
CO_2	13.82	0.19	0.56	-0.02	-0.36	-0.09	0.01	0.02	0.01	0.04
O_2	3.45	0.23	0.16	-0.10	0.27	-0.15	0.01	-0.02	0.02	-0.01
Temperature	136.20	-0.03	35.22	-0.05	-18.29	0.96	0.02	2.55	-0.28	0.37
Velocity	6.54	-2.66	4.48	0.27	-1.42	0.38	0.01	0.11	-0.05	-0.01

Table 61 (Continued)

Cubic Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2+b_6x_1^3+b_7x_2^3+b_8x_1^2x_2+b_9x_1x_2^2$$

	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
Widows Creek Unit 7 (Duct B)										
SO_2	2293.60	-51.35	-109.82	0.38	85.95	67.37	0.28	-28.87	-8.54	2.35
NO	319.22	12.57	20.79	-1.64	-8.34	0.41	0.02	-0.75	-0.02	0.53
CO_2	12.62	0.39	0.99	-0.07	-0.39	-0.03	0.00	-0.01	-0.01	0.02
O_2	5.19	-0.34	-0.23	0.06	-0.15	-0.03	0.00	0.12	0.01	-0.04
Temperature	122.45	-4.89	55.39	0.07	-25.15	-0.87	0.01	2.91	-0.23	0.95
Velocity	4.86	-1.96	5.52	0.25	-2.32	0.51	0.00	0.27	-0.07	0.00
E. C. Gaston Unit 5 (Duct A)										
SO_2	564.35	108.95	167.23	-8.11	114.01	-31.16	0.18	-67.12	0.35	7.08
NO	385.15	39.71	113.49	-3.47	-46.74	-12.01	0.05	5.82	0.81	-0.02
CO_2	9.34	0.39	2.29	0.03	-0.51	-0.28	0.00	-0.01	0.02	0.01
O_2	8.97	-0.64	-2.93	0.02	0.63	0.38	0.00	0.08	-0.02	-0.01
Temperature	133.47	5.05	42.46	-0.55	-25.75	-4.44	0.00	5.24	0.21	0.57
Velocity	17.04	3.39	-19.47	-0.22	20.35	-2.00	0.01	-5.77	0.01	0.37
E. C. Gaston Unit 5 (Duct B)										
SO_2	691.29	82.78	273.78	-4.27	-91.24	-28.89	-0.03	5.61	1.18	2.33
NO	298.36	48.70	182.39	-5.66	-104.71	-13.18	0.20	18.21	0.67	1.09
CO_2	8.70	1.00	4.83	-0.06	-2.38	-0.43	0.00	0.32	0.02	0.04
O_2	9.65	-1.35	-4.73	0.13	2.14	0.49	0.00	-0.26	-0.03	-0.04
Temperature	95.23	2.96	9.11	0.48	2.71	-1.75	-0.04	-2.53	-0.08	0.25
Velocity	14.37	2.25	-15.50	-0.19	7.63	0.70	0.01	-0.99	-0.03	-0.29

Table 61 (Continued)

Cubic Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2+b_6x_1^3+b_7x_2^3+b_8x_1^2x_2+b_9x_1x_2^2$$

	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
Barry Unit 4 (Duct A)										
SO_2	1209.20	238.15	134.80	-78.14	-53.88	-25.75	7.75	8.10	5.57	0.48
NO	323.23	-29.93	-19.11	4.06	6.30	12.36	0.41	-0.84	-1.58	-0.69
CO_2	12.26	-0.85	1.43	0.86	-0.69	0.05	-0.16	0.09	-0.03	0.02
O_2	7.10	-0.38	-1.11	-0.04	0.48	0.05	0.03	-0.07	-0.01	0.00
Temperature	159.65	-25.20	-3.90	13.94	1.43	6.37	-2.11	-0.08	-0.46	-0.89
Velocity	16.85	-2.42	-2.30	0.68	0.78	-0.50	-0.007	-0.13	-0.08	0.19
Barry Unit 4 (Duct B)										
SO_2	1161.40	358.31	-24.99	-124.00	16.83	-5.15	12.24	-0.16	4.41	-5.09
NO	272.78	73.72	-0.70	-34.56	2.58	-5.49	4.40	-0.61	0.59	1.16
CO_2	11.26	1.67	0.19	-0.27	0.03	-0.22	-0.02	0.00	0.02	0.02
O_2	8.31	-2.61	-0.34	0.88	0.01	0.18	-0.08	0.00	0.00	-0.02
Temperature	118.46	14.29	9.92	-8.47	-0.52	-3.49	1.32	-0.16	0.17	0.52
Velocity	19.64	-6.06	-5.84	1.77	1.94	1.11	-0.12	-0.23	-0.14	-0.12
Barry Unit 5 (Duct A)										
SO_2	1646.10	215.86	138.27	-28.15	-107.41	23.96	1.11	17.08	-2.02	-1.26
NO	242.78	35.07	0.62	-3.49	6.48	-0.84	0.01	-1.45	0.04	-0.27
CO_2	9.74	1.78	1.17	-0.23	-0.73	-0.05	0.01	0.15	0.00	0.02
O_2	8.60	-1.63	-0.80	0.20	0.43	0.05	-0.01	-0.08	0.00	-0.02
Temperature	129.01	0.90	-1.01	-0.53	0.98	0.86	0.02	-0.68	-0.03	-0.12
Velocity	4.58	0.40	0.28	-0.03	0.60	-0.27	0.00	-0.19	0.01	0.04

Table 61 (Continued)

Cubic Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2+b_6x_1^3+b_7x_2^3+b_8x_1^2x_2+b_9x_1x_2^2$$

	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
Barry Unit 5 (Duct B)										
SO_2	1804.70	-102.14	126.11	30.64	-65.42	-8.19	-2.31	5.28	-0.27	5.16
NO	248.36	-5.42	20.79	2.87	-10.49	-2.63	-0.25	1.39	-0.03	0.99
CO_2	9.34	0.49	1.58	0.00	-0.67	-0.21	-0.01	-0.06	0.00	0.07
O_2	9.02	-0.46	-1.08	-0.02	0.22	0.29	0.01	0.00	-0.01	-0.05
Temperature	102.87	-3.03	6.20	1.30	1.33	0.90	-0.08	-1.84	-0.04	-0.13
Velocity	3.48	0.63	-1.65	-0.06	1.39	-0.01	0.00	-0.31	0.00	-0.01
Morgantown Unit 1 (Duct A)										
SO_2	1165.70	-25.58	61.20	3.84	-72.55	41.83	-0.38	22.40	0.15	-14.45
NO	355.41	-23.75	-89.20	3.28	70.38	18.26	-0.18	-15.69	-0.44	-4.49
CO_2	12.66	-0.25	-0.17	0.02	-0.08	0.59	0.00	0.07	0.00	-0.19
O_2	5.21	0.26	-0.28	-0.03	0.61	-0.58	0.00	-0.23	0.00	0.19
Temperature	167.28	-6.04	1.94	0.18	-4.01	1.26	0.00	1.24	0.00	-0.11
Velocity	31.64	-4.08	-13.60	0.21	8.77	1.35	0.00	-2.61	-0.12	0.07
Morgantown Unit 1 (Duct B)										
SO_2	987.46	7.20	59.53	0.68	40.27	2.54	-0.11	-26.71	-0.83	4.22
NO	308.46	-2.00	39.76	1.95	-13.14	-2.05	-0.14	-1.72	-0.05	2.55
CO_2	11.99	0.09	-1.06	-0.04	1.27	0.22	0.00	-0.40	-0.01	-0.02
O_2	5.93	-0.15	1.14	0.03	-1.62	-0.19	0.00	0.52	0.00	0.02
Temperature	152.47	-0.94	-1.20	-0.96	-6.82	3.86	0.07	2.96	-0.14	-0.69
Velocity	20.29	-4.21	-0.19	0.67	-2.55	0.74	-0.03	0.24	-0.06	-0.09

Table 61 (Continued)

Cubic Regression Equation Coefficients

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1^2 + b_4 x_2^2 + b_5 x_1 x_2 + b_6 x_1^3 + b_7 x_2^3 + b_8 x_1^2 x_2 + b_9 x_1 x_2^2$$

	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
Navajo Unit 1 (Duct A)										
SO_2	395.42	-43.89	66.00	6.66	-28.45	2.84	-0.11	3.11	-1.15	1.00
NO	241.81	7.37	8.41	-0.50	-1.85	-0.76	0.00	0.17	0.15	-0.15
CO_2	13.30	-0.13	0.55	0.04	-0.25	-0.01	0.00	0.02	0.00	0.02
O_2	5.59	0.01	-0.01	0.03	0.10	-0.08	0.00	-0.01	0.01	0.00
Temperature	177.38	-28.61	-25.23	9.96	10.01	2.35	-1.01	-1.07	0.36	-1.05
Velocity	10.98	0.01	1.11	-0.48	-0.53	-0.14	0.01	0.07	-0.02	0.03
Navajo Unit 1 (Duct B)										
SO_2	399.09	-4.92	25.72	3.29	7.47	-10.91	-0.47	-3.23	0.28	2.12
NO	238.70	6.34	-6.55	-1.86	1.05	0.79	0.13	0.12	0.16	-0.27
CO_2	12.54	-0.09	-0.29	0.01	0.06	0.08	0.00	0.00	0.00	-0.01
O_2	6.88	-0.05	0.06	0.01	-0.03	-0.02	0.00	0.00	0.00	0.00
Temperature	97.08	18.72	24.26	-5.70	-8.88	-0.35	0.51	1.00	0.03	0.01
Velocity	7.26	1.38	2.49	-0.30	-1.04	-0.48	0.05	0.11	-0.08	0.16
Navajo Unit 1 (Duct C)										
SO_2	292.55	43.44	9.73	-9.83	18.27	-14.33	0.66	-3.51	1.50	0.34
NO	275.20	-9.95	-0.38	2.57	1.53	0.99	-0.18	-0.31	-0.13	-0.13
CO_2	12.34	0.00	0.23	-0.01	0.03	0.00	0.00	-0.02	0.00	0.00
O_2	7.13	-0.26	-0.45	0.05	0.08	0.05	0.00	0.00	0.00	0.01
Temperature	131.52	-5.23	0.06	2.80	5.70	-3.19	-0.31	-1.33	0.24	0.34
Velocity	14.12	-0.98	-3.83	0.15	0.46	0.74	-0.03	0.03	0.01	-0.12

Table 61 (Continued)

Cubic Regression Equation Coefficients

$$y = b_0+b_1x_1+b_2x_2+b_3x_1^2+b_4x_2^2+b_5x_1x_2+b_6x_1^3+b_7x_2^3+b_8x_1^2x_2+b_9x_1x_2^2$$

	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
Navajo Unit 1 (Duct D)										
SO_2	204.01	40.02	166.84	0.50	-16.10	-42.70	-0.32	-3.65	1.48	6.36
NO	246.67	20.99	-1.07	-6.89	0.09	-0.90	0.64	0.24	0.30	-0.35
CO_2	11.84	0.45	0.29	-0.17	-0.12	-0.07	0.02	0.01	0.00	0.01
O_2	7.19	-0.41	-0.16	0.14	-0.02	-0.07	-0.01	0.01	-0.01	0.00
Temperature	152.10	0.70	-4.13	0.21	2.77	0.85	-0.05	-0.41	0.02	-0.28
Velocity	10.26	-1.34	0.81	0.11	-1.78	1.07	0.01	0.30	-0.07	-0.08
Navajo Unit 1 (Stack at 725 MW)										
SO_2	444.29	-10.83	6.18	-0.34	3.22	0.00	1.24	-0.79	0.00	0.00
NO	241.07	-12.84	-3.64	-0.36	2.78	0.00	1.16	-0.52	0.00	0.00
CO_2	12.18	0.76	0.23	-0.06	-0.05	0.00	-0.09	-0.02	0.00	0.00
O_2	6.25	0.10	-0.12	0.00	-0.03	0.00	-0.01	0.02	0.00	0.00
Temperature	139.25	-0.37	-0.43	0.00	0.08	0.00	0.04	0.02	0.00	0.00
Velocity	33.29	0.53	0.78	-0.12	-0.07	0.00	-0.12	-0.15	0.00	0.00
Navajo Unit 1 (Stack at 800 MW)										
SO_2	445.20	-2.63	-1.86	1.69	1.03	0.00	0.07	0.33	0.00	0.00
NO	244.63	-2.19	7.11	0.36	-0.13	0.00	0.21	-0.56	0.00	0.00
CO_2	12.77	-0.14	-0.19	0.00	-0.03	0.00	0.01	0.02	0.00	0.00
O_2	6.13	0.21	0.06	0.03	0.02	0.00	-0.02	-0.01	0.00	0.00
Temperature	149.10	0.24	0.10	0.01	-0.01	0.00	-0.02	-0.01	0.00	0.00
Velocity	45.21	2.01	1.40	-0.11	-0.55	0.00	-0.28	-0.18	0.00	0.00

4.2.2 Sample Contour Diagrams

Figures 27-50 present computer printed contour diagrams developed for two representative boilers tested in this program. The contours shown are for the No. 1 boiler at the Morgantown station of the Potomac Electric Power Company and boiler No. 5 at the E. C. Gaston station of the Southern Electric Generating Company. The coding scales of the contours and the multiple regression equation used to plot the contours are given below each contour. As can be seen, the contours were developed using a quadratic model. Stratification contours developed by TRW (6), based on data obtained by Exxon in stratification measured on Widows Creek Unit 7, are based upon a higher order model. These contours indicate more run to run variation than the second degree model used in this report. Although the directional trends shown by the higher order model are similar to those exhibited by the contour diagrams of the quadratic model, the fine perturbations resulting from the higher order model are presumably due to short time fluctuations. Therefore, the quadratic contours based on duplicate traverses of the same duct appear to be the preferred time average representation of the data. It should also be noted that the duct dimensions in Figures 27-50 are not drawn to scale on the contour diagrams. The abscissa scales are considerably compressed relative to the ordinate scales and, therefore, the actual stratifications across the duct are less pronounced than suggested by a visual inspection of the contour diagrams.

Conclusions drawn from the stratification contour diagrams in Figures 27-50 are as follows:

- CO_2, NO, and SO_2 concentrations as expected, follow the O_2 concentration (i.e., where the O_2 concentration is lowest the concentration of the other species are highest and vice-versa because of dilution).

- O_2 stratification contours are affected by air heater leakage and direction of rotation of the air heater as indicated by the consistent pattern of high O_2 concentration and higher degree of O_2 stratification along duct walls that correspond to the upstream position of flue gas/air contact in the air heater.

- O_2 stratification contours can also be affected by leakage of air into the ductwork (not in the air heater) but this appears to be minimal in the units tested.

- As expected, O_2 concentrations are lowest in the center portions of the duct and increase toward the sidewalls as affected by either air heater leakage or infiltration of air into the ducts.

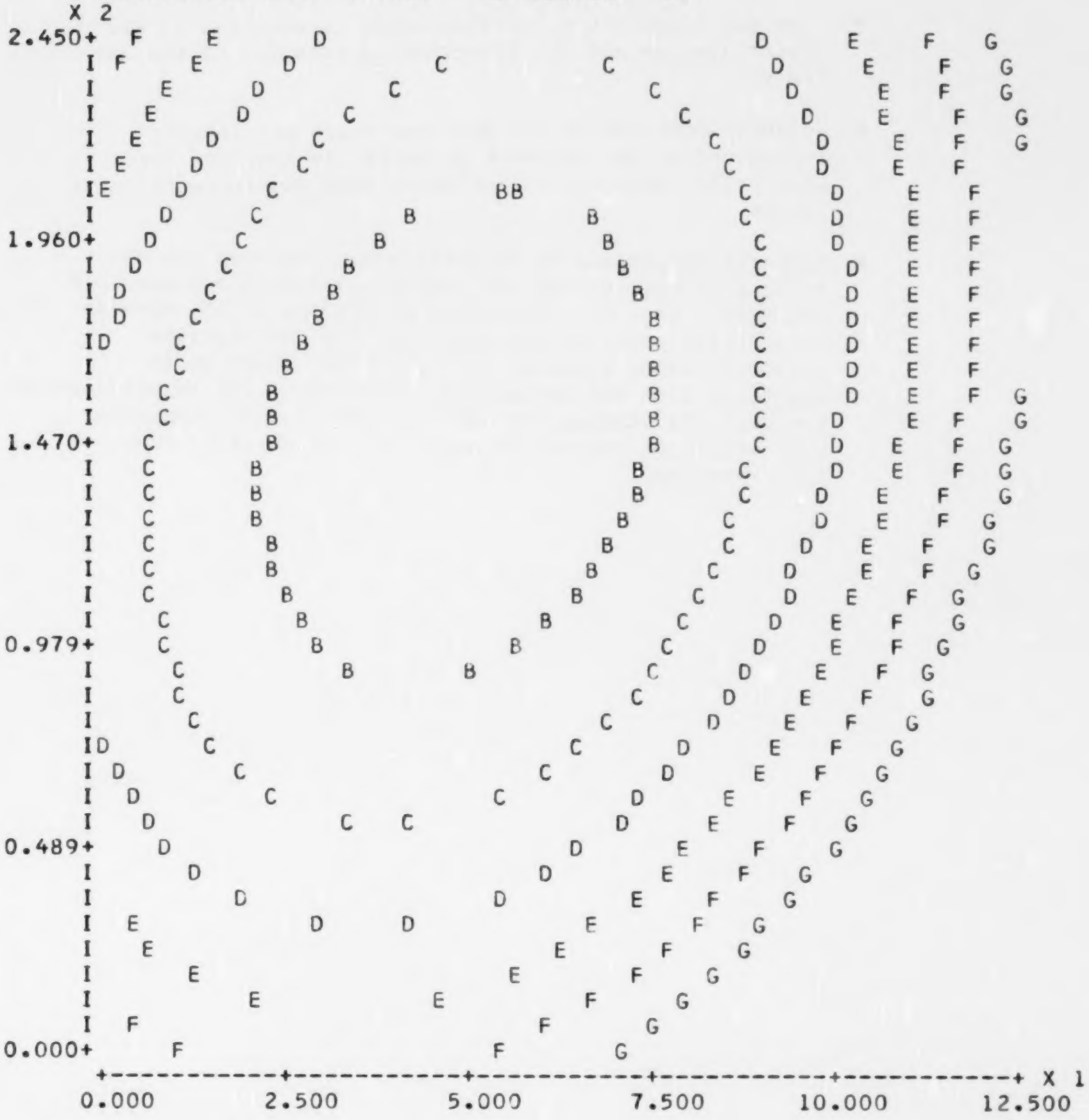
- Flue gas temperature stratification is affected by air heater leakage and the direction of rotation of the air heater.

- Velocity profiles in the flue gas ducts are largely influenced by the ductwork geometry (ie downward bends show higher velocity on bottom of duct due to centrifugal forces.

- Temporal variations in stratification contours are minor as long as boiler load and combustion conditions are held constant. This is illustrated in Figures 51-53, showing O_2 stratification in the same duct for two separate traverses taken approximately 4-5 hours apart under identical load and combustion conditions. The stratification contours are similar for each run and for the composite stratification contour is based on data obtained from both traverses.

Figure 27

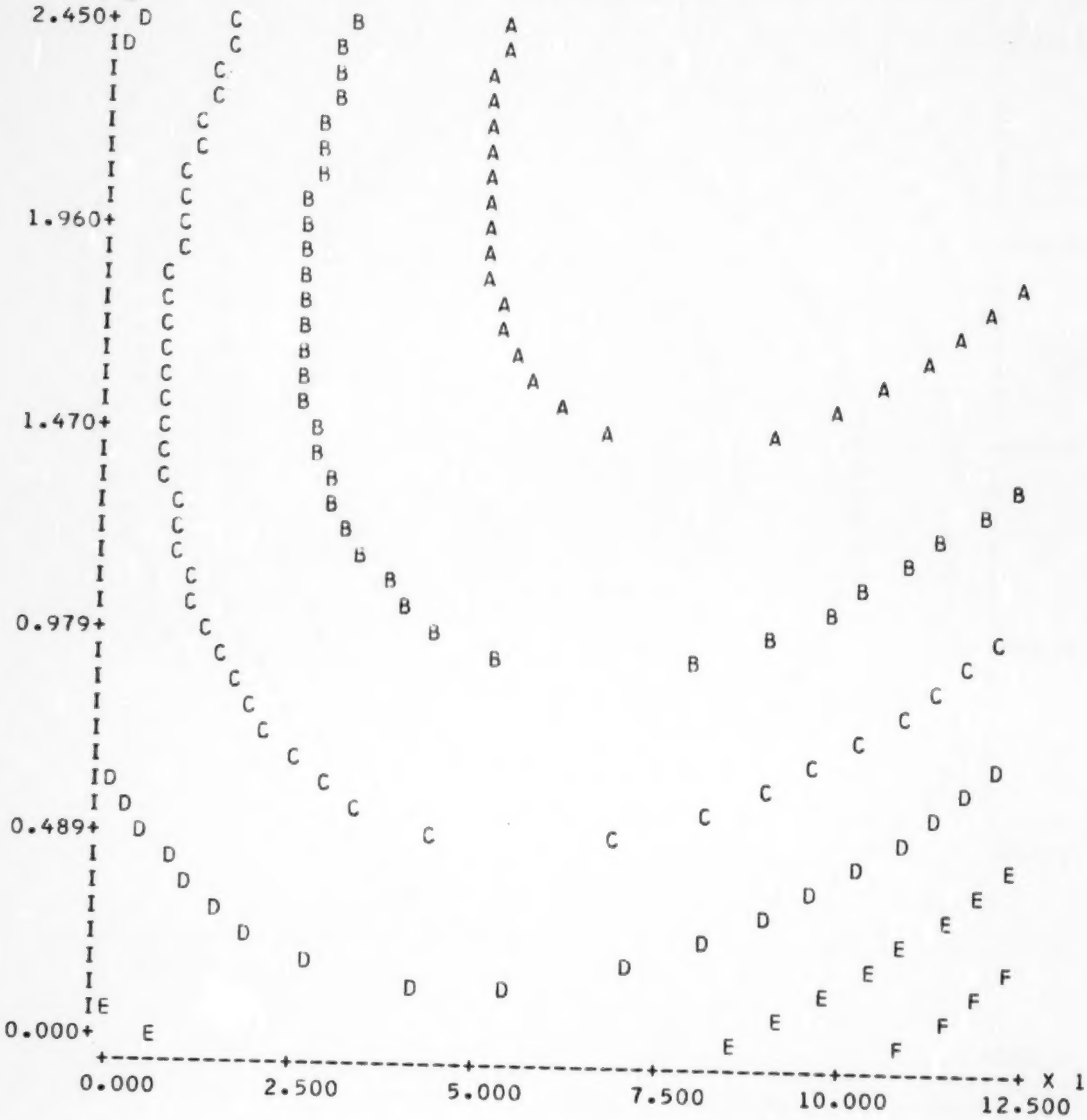
MORGANTOWN UNIT 1 (1A) - O2 CONTOUR (%)



```
CODING OF           RESPONSE =
CONTOURS          0.67700E 01
A=    4.000      -0.32000E 00(X   1)
B=    4.500      -0.24700E 01(X   2)
C=    5.000       0.50000E-01(X   1)(X   1)
D=    5.500       0.10100E 01(X   2)(X   2)
E=    6.000      -0.11000E 00(X   1)(X   2)
F=    6.500
G=    7.000
```

Figure 28

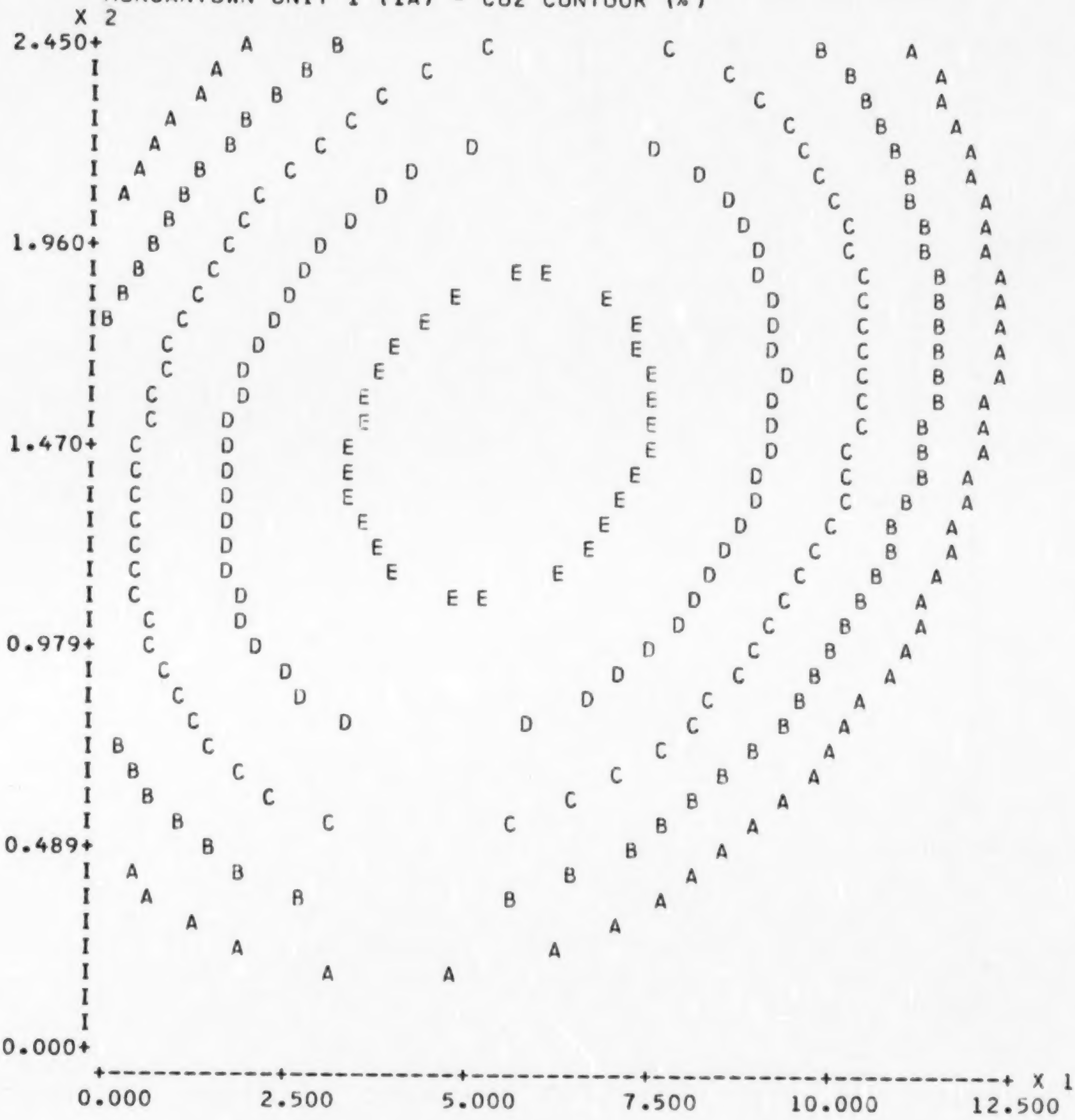
MORGANTOWN UNIT 1 (1B) - O2 CONTOUR (%)



```
CODING OF                RESPONSE =
CONTOURS               0.65900E 01
A=     4.500          -0.18000E 00(X  1)
B=     5.000          -0.12000E 01(X  2)
C=     5.500           0.20000E-01(X  1)(X  1)
D=     6.000           0.40000E 00(X  2)(X  2)
E=     6.500          -0.90000E-01(X  1)(X  2)
F=     7.000
G=     7.500
```

Figure 29

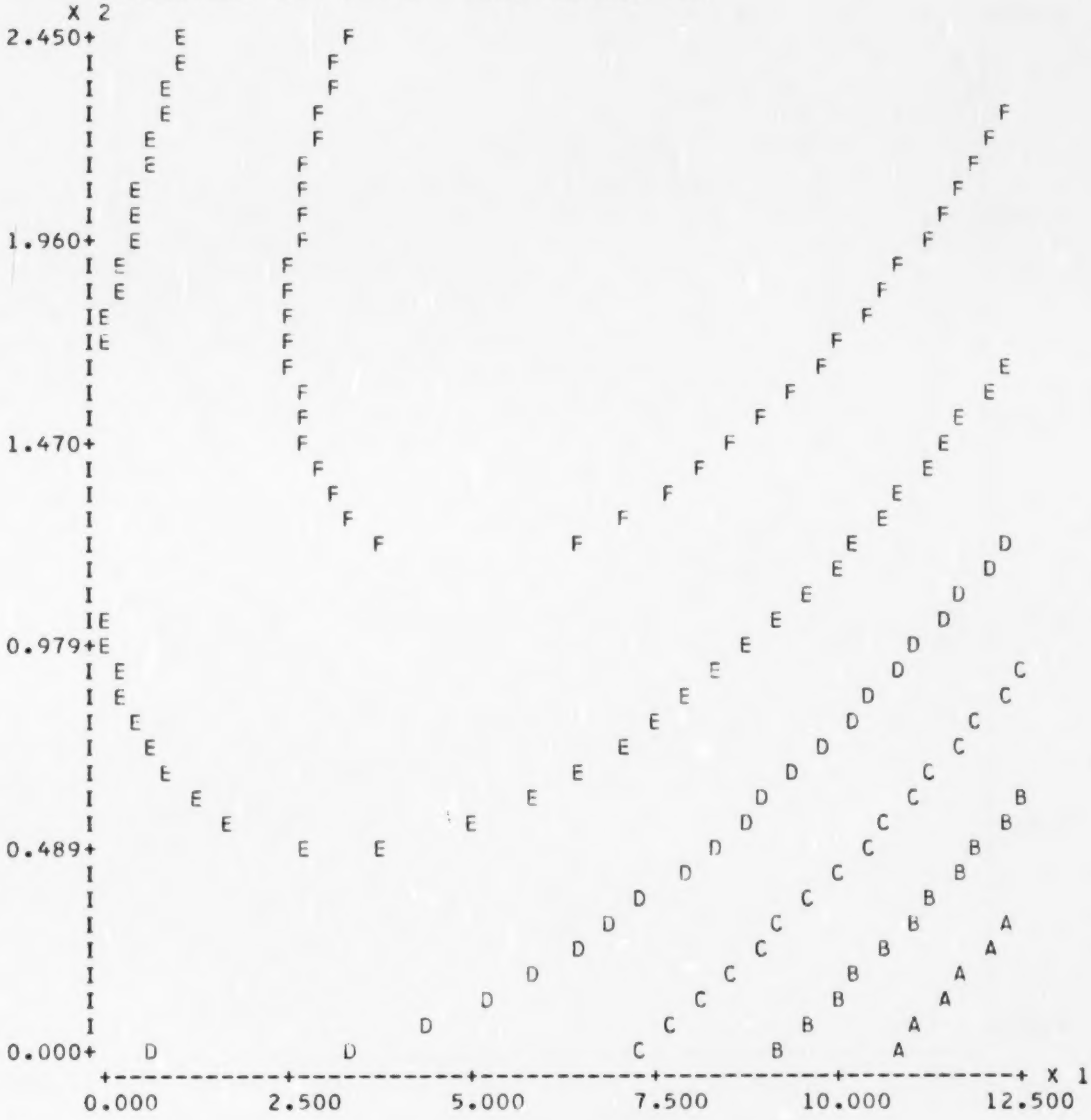
MORGANTOWN UNIT 1 (1A) - CO2 CONTOUR (%)



```
CODING OF          RESPONSE =
CONTOURS         0.10950E 02
A=   12.000      0.30000E 00(X  1)
B=   12.400      0.26600E 01(X  2)
C=   12.800     -0.40000E-01(X  1)(X  1)
D=   13.200     -0.10500E 01(X  2)(X  2)
E=   13.600      0.90000E-01(X  1)(X  2)
F=   14.000
G=   14.399
H=   14.799
```

Figure 30

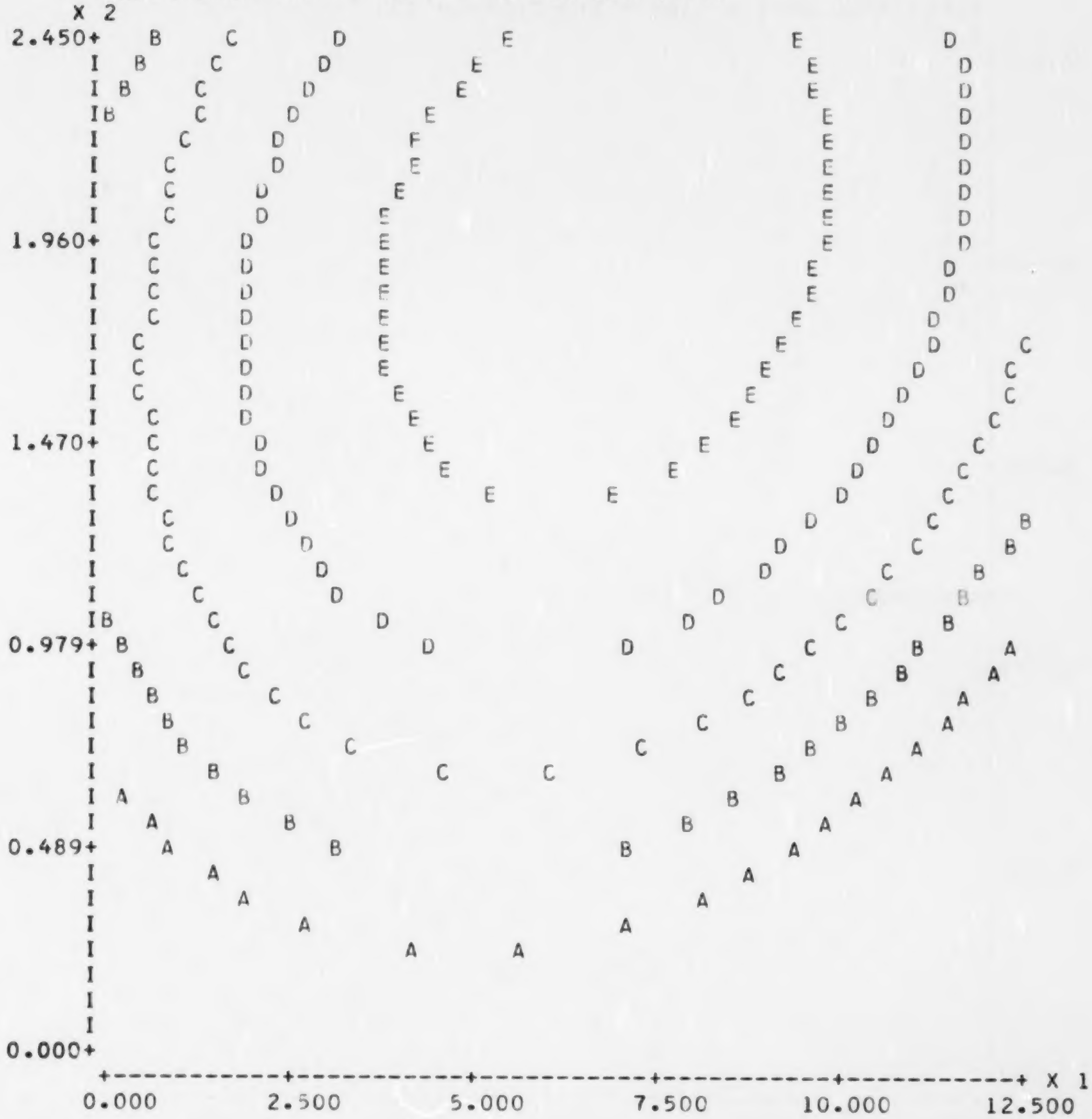
MORGANTOWN UNIT 1 (1B) - CO2 CONTOUR (%)



```
CODING OF            RESPONSE =
CONTOURS            0.11460E 02
A=   10.000         0.80000E-01(X  1)
B=   10.500         0.84000E 00(X  2)
C=   11.000        -0.20000E-01(X  1)(X  1)
D=   11.500        -0.31000E 00(X  2)(X  2)
E=   12.000         0.10000E 00(X  1)(X  2)
F=   12.500
G=   13.000
```

Figure 31

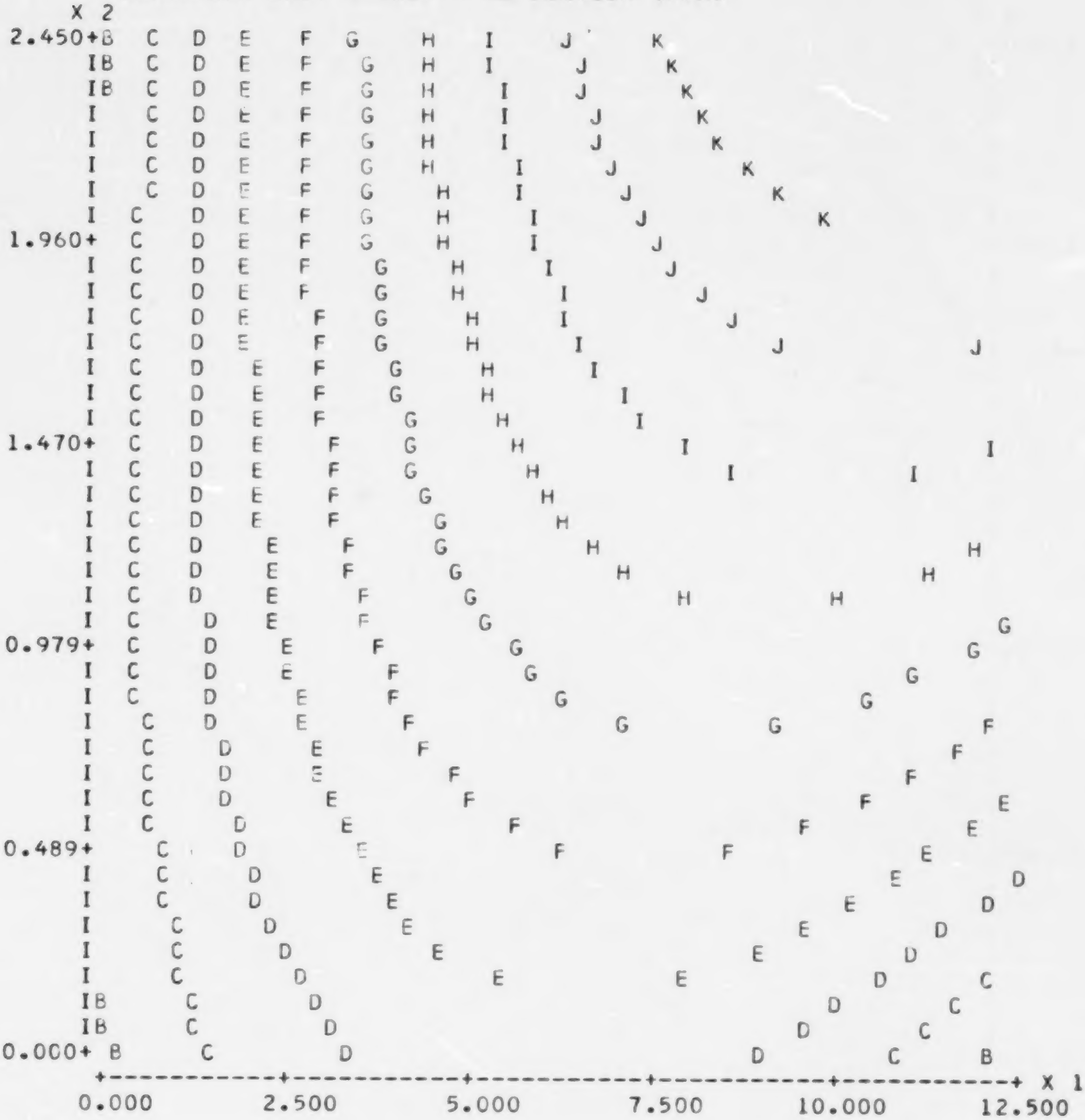
MORGANTOWN UNIT 1 (1A) - NO CONTOUR (PPM)



```
CODING OF          RESPONSE =
CONTOURS          0.27150E 03
A= 300.000        0.64900E 01(X  1)
B= 310.000        0.53830E 02(X  2)
C= 320.000       -0.71000E 00(X  1)(X  1)
D= 330.000       -0.16430E 02(X  2)(X  2)
E= 340.000        0.15900E 01(X  1)(X  2)
F= 350.000
G= 360.000
H= 370.000
I= 380.000
J= 390.000
K= 400.000
```

Figure 32

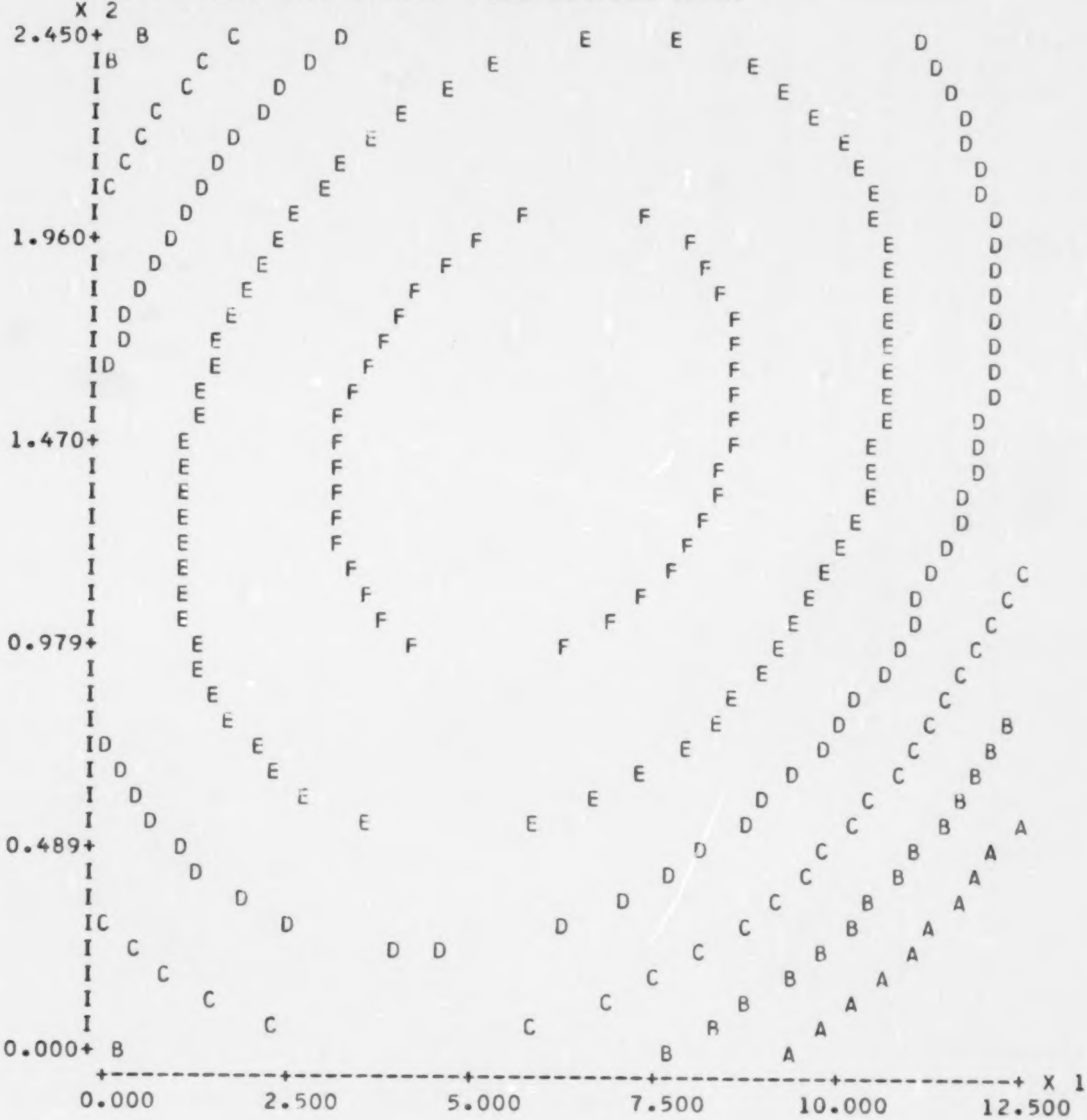
MORGANTOWN UNIT 1 (1B) - NO CONTOUR (PPM)



```
CODING OF              RESPONSE =
CONTOURS              0.30885E 03
A=  300.000           0.86000E 01(X  1)
B=  310.000           0.96400E 01(X  2)
C=  320.000          -0.70000E 00(X  1)(X  1)
D=  330.000          -0.39800E 01(X  2)(X  2)
E=  340.000           0.35800E 01(X  1)(X  2)
F=  350.000
G=  360.000
H=  370.000
I=  380.000
J=  390.000
K=  400.000
```

Figure 33

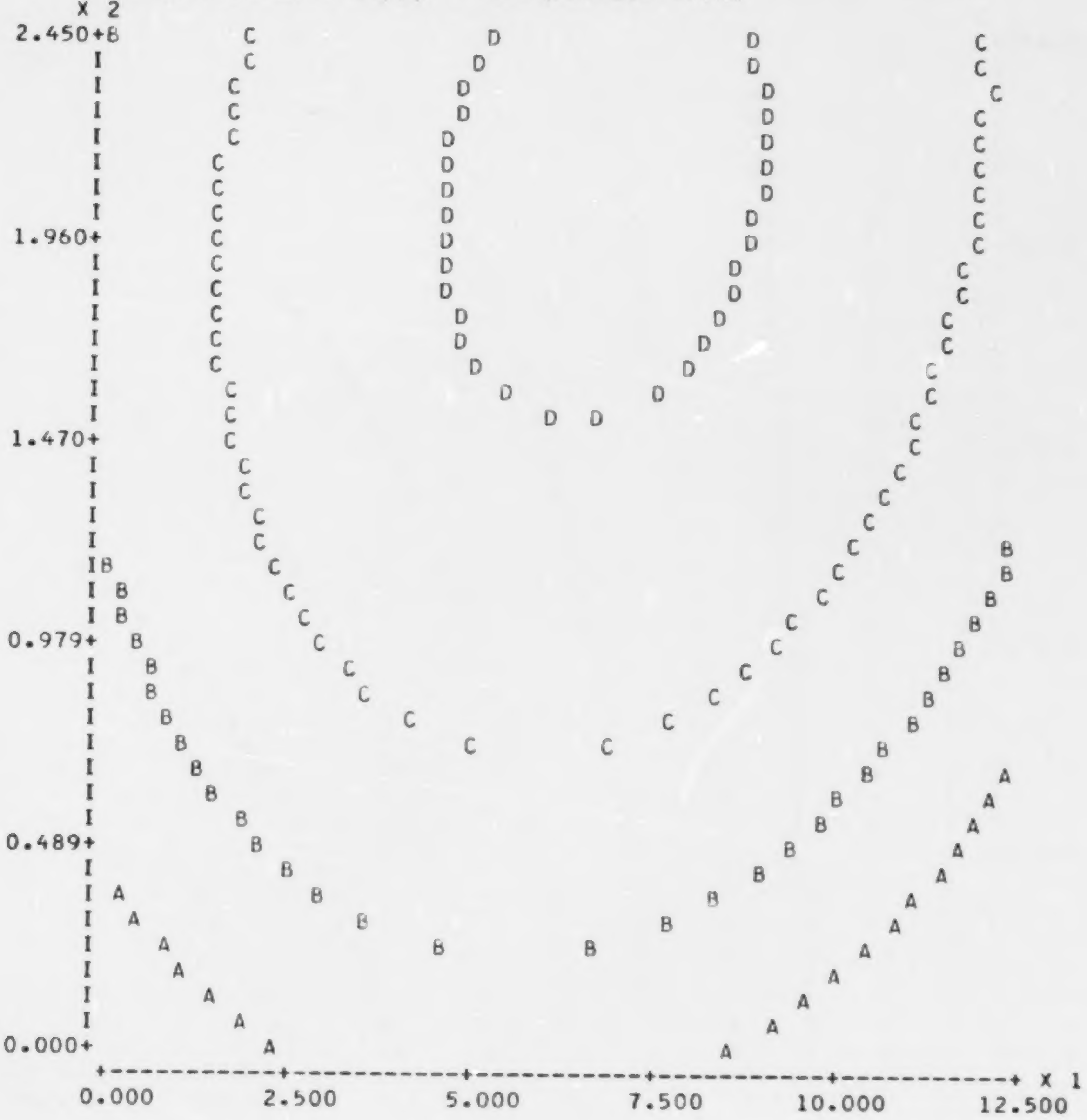
MORGANTOWN UNIT 1 (1A) - SO2 CONTOUR (PPM)



```
CODING OF            RESPONSE =
CONTOURS           0.10433E 04
A=1000.000         0.26850E 02(X  1)
B=1050.000         0.20473E 03(X  2)
C=1100.000        -0.33800E 01(X  1)(X  1)
D=1150.000        -0.85270E 02(X  2)(X  2)
E=1200.000         0.85100E 01(X  1)(X  2)
F=1250.000
G=1300.000
```

Figure 34

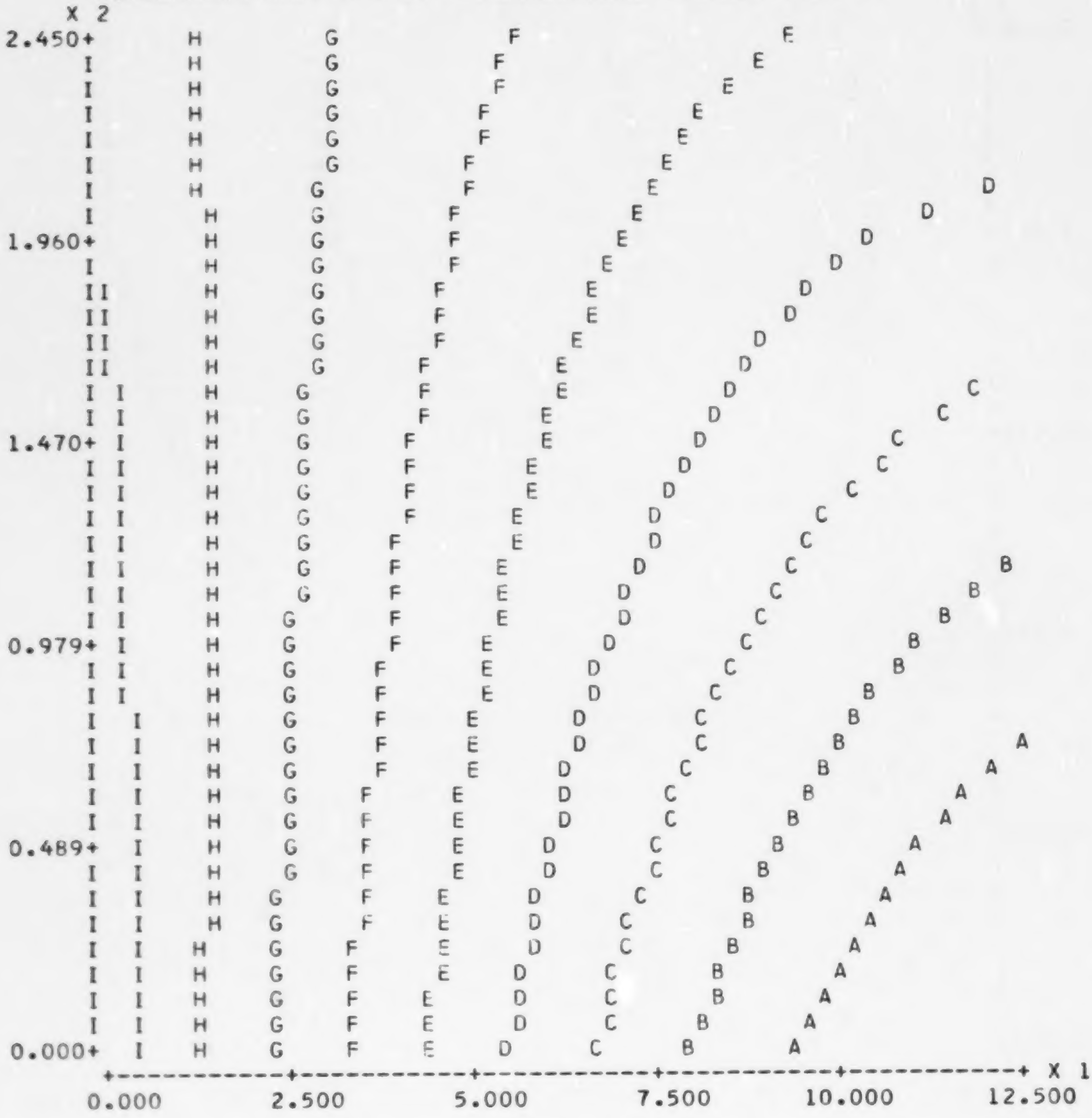
MORGANTOWN UNIT 1 (1B) - SO2 CONTOUR (PPM)



```
CODING OF         RESPONSE =
CONTOURS         0.95621E 03
A=1000.000       0.24410E 02(X  1)
B=1050.000       0.11615E 03(X  2)
C=1100.000      -0.22500E 01(X  1)(X  1)
D=1150.000      -0.31880E 02(X  2)(X  2)
E=1200.000       0.27500E 01(X  1)(X  2)
```

Figure 35

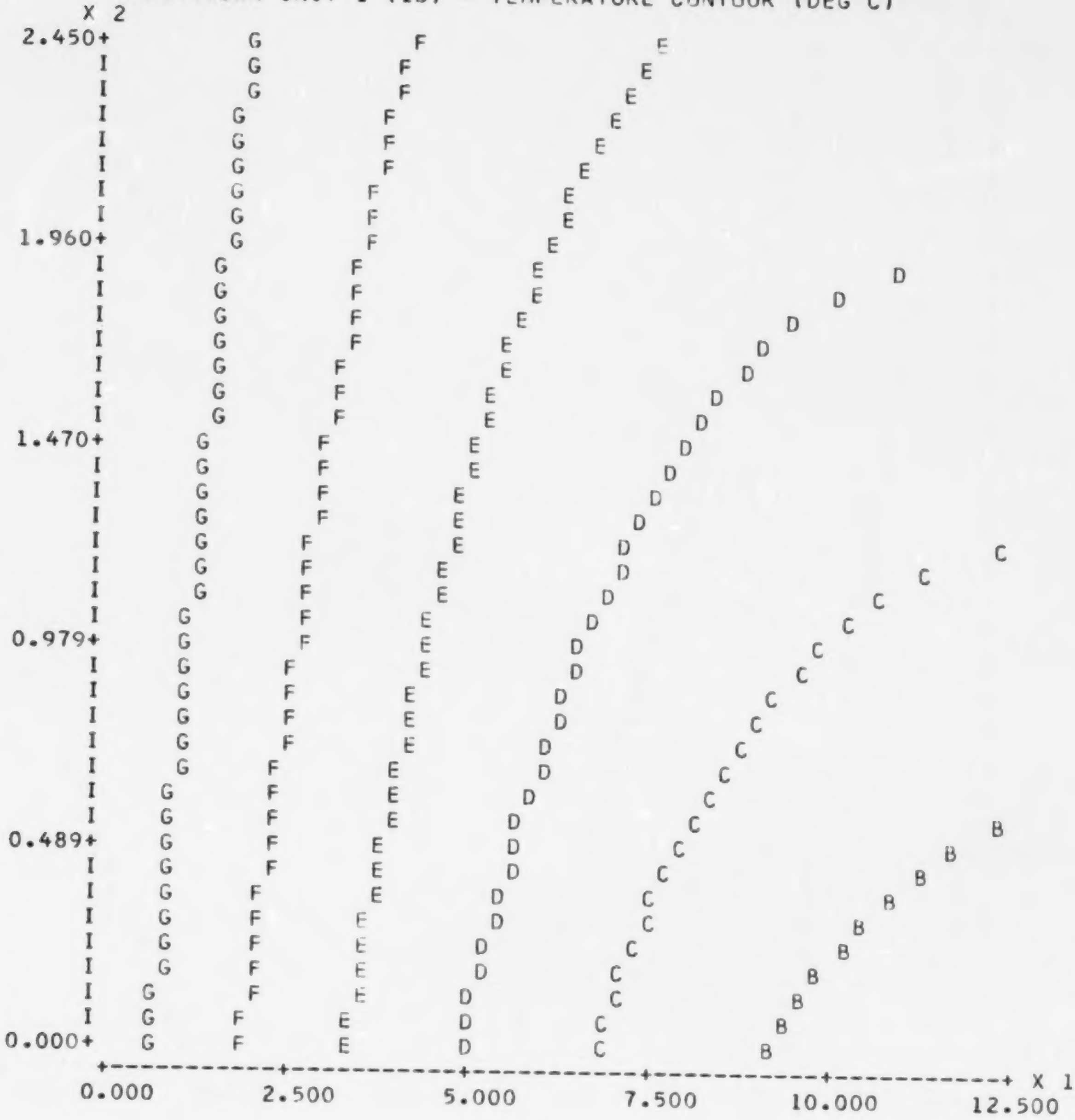
MORGANTOWN UNIT 1 (1A) - TEMPERATURE CONTOUR (DEG C)



```
CODING OF         RESPONSE =
CONTOURS        0.16738E 03
A= 125.000     -0.57100E 01(X  1)
B= 130.000     -0.90000E 00(X  2)
C= 135.000      0.13000E 00(X  1)(X  1)
D= 140.000     -0.20000E 00(X  2)(X  2)
E= 145.000      0.10100E 01(X  1)(X  2)
F= 150.000
G= 155.000
H= 160.000
I= 165.000
```

Figure 36

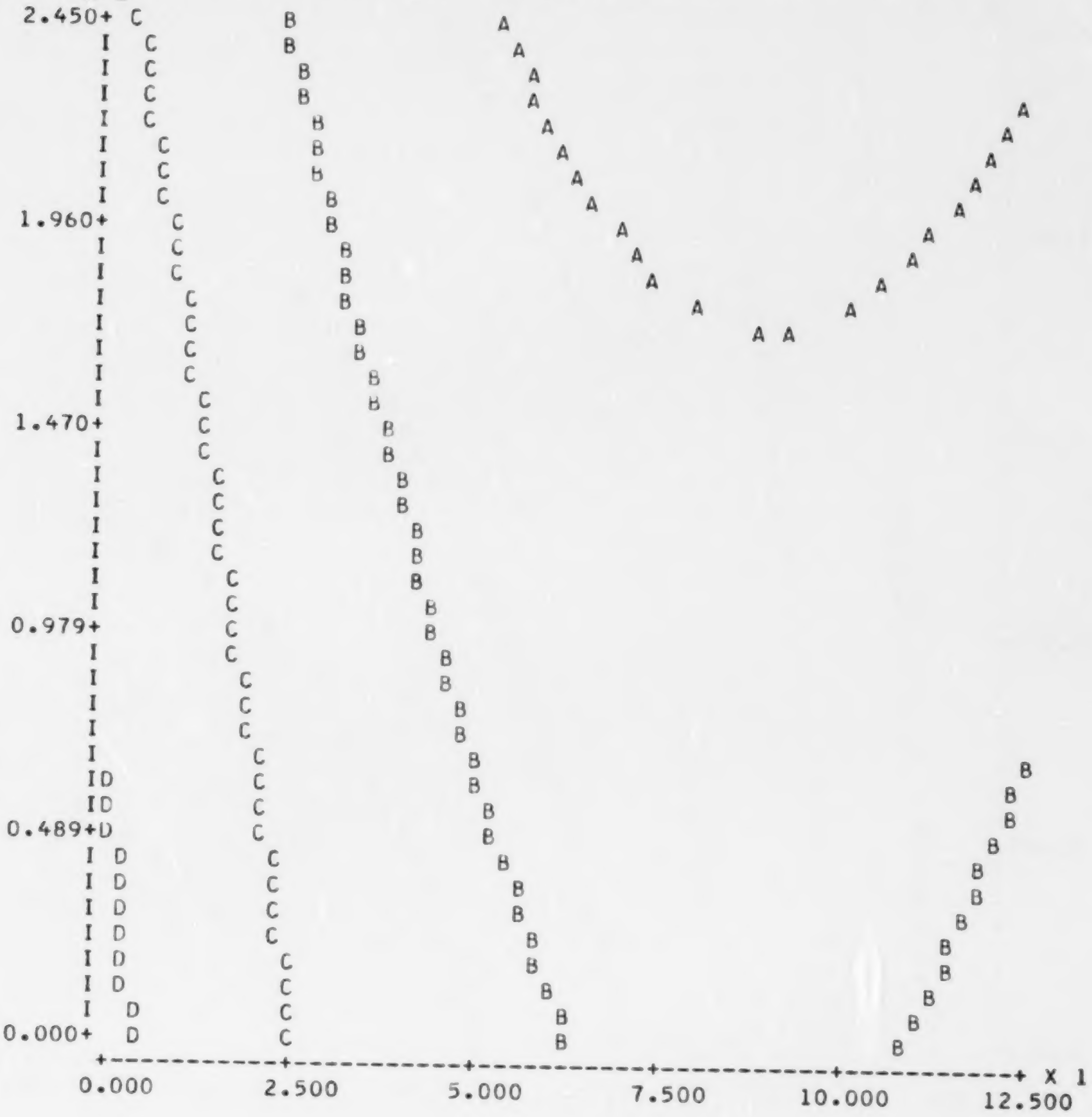
MORGANTOWN UNIT 1 (1B) - TEMPERATURE CONTOUR (DEG C)



```
CODING OF                 RESPONSE =
CONTOURS                0.15284E 03
A= 120.000             -0.43200E 01(X  1)
B= 125.000              0.13600E 01(X  2)
C= 130.000              0.14000E 00(X  1)(X  1)
D= 135.000             -0.16000E 00(X  2)(X  2)
E= 140.000              0.51000E 00(X  1)(X  2)
F= 145.000
G= 150.000
```

Figure 37

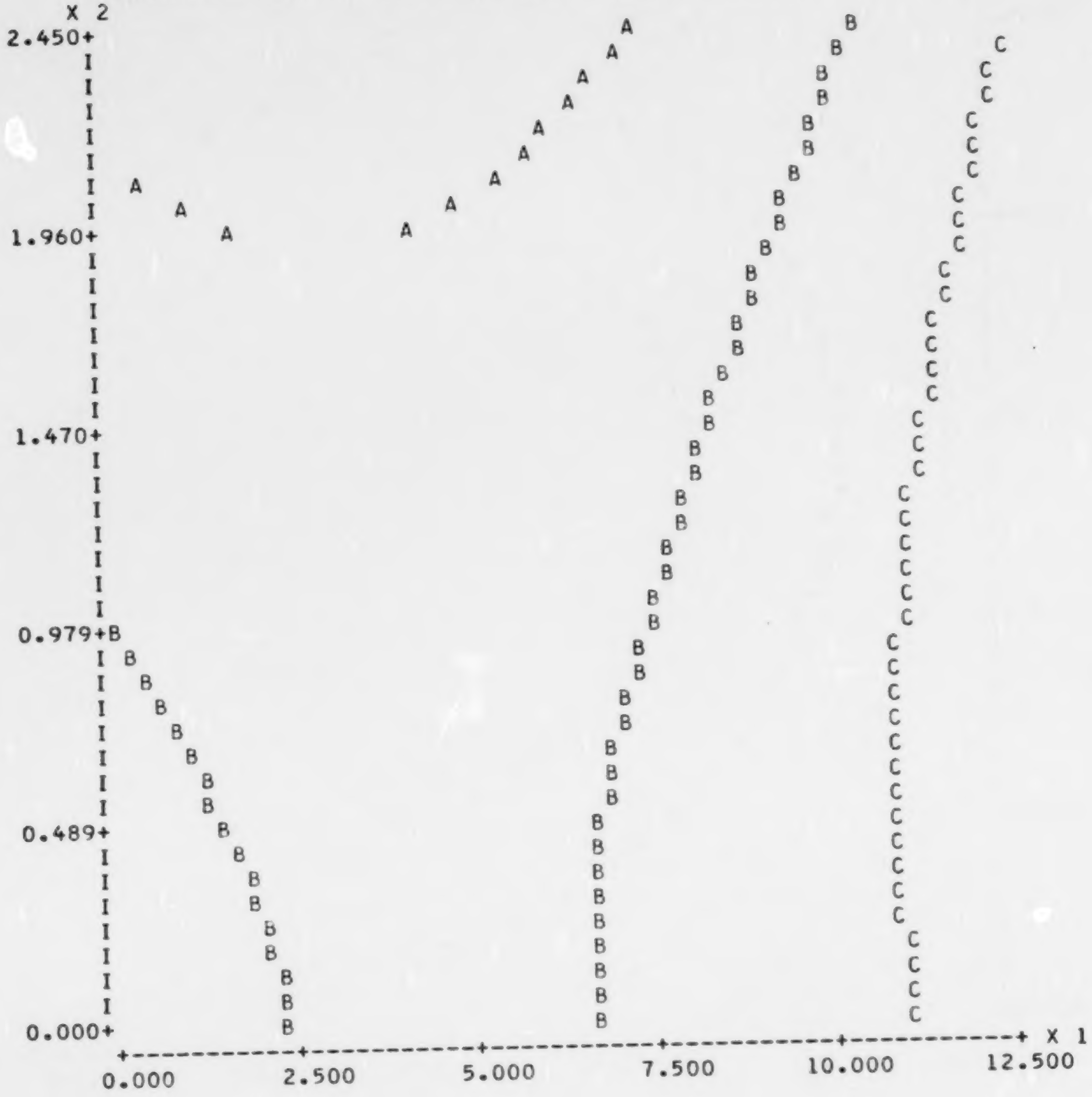
MORGANTOWN UNIT 1 (1A) - VELOCITY CONTOUR (M/S)



```
CODING OF              RESPONSE =
CONTOURS             0.25980E 02
A=   10.000         -0.27500E 01(X  1)
B=   15.000         -0.13600E 01(X  2)
C=   20.000          0.16000E 00(X  1)(X  1)
D=   25.000         -0.32000E 00(X  2)(X  2)
                    -0.60000E-01(X  1)(X  2)
```

Figure 38

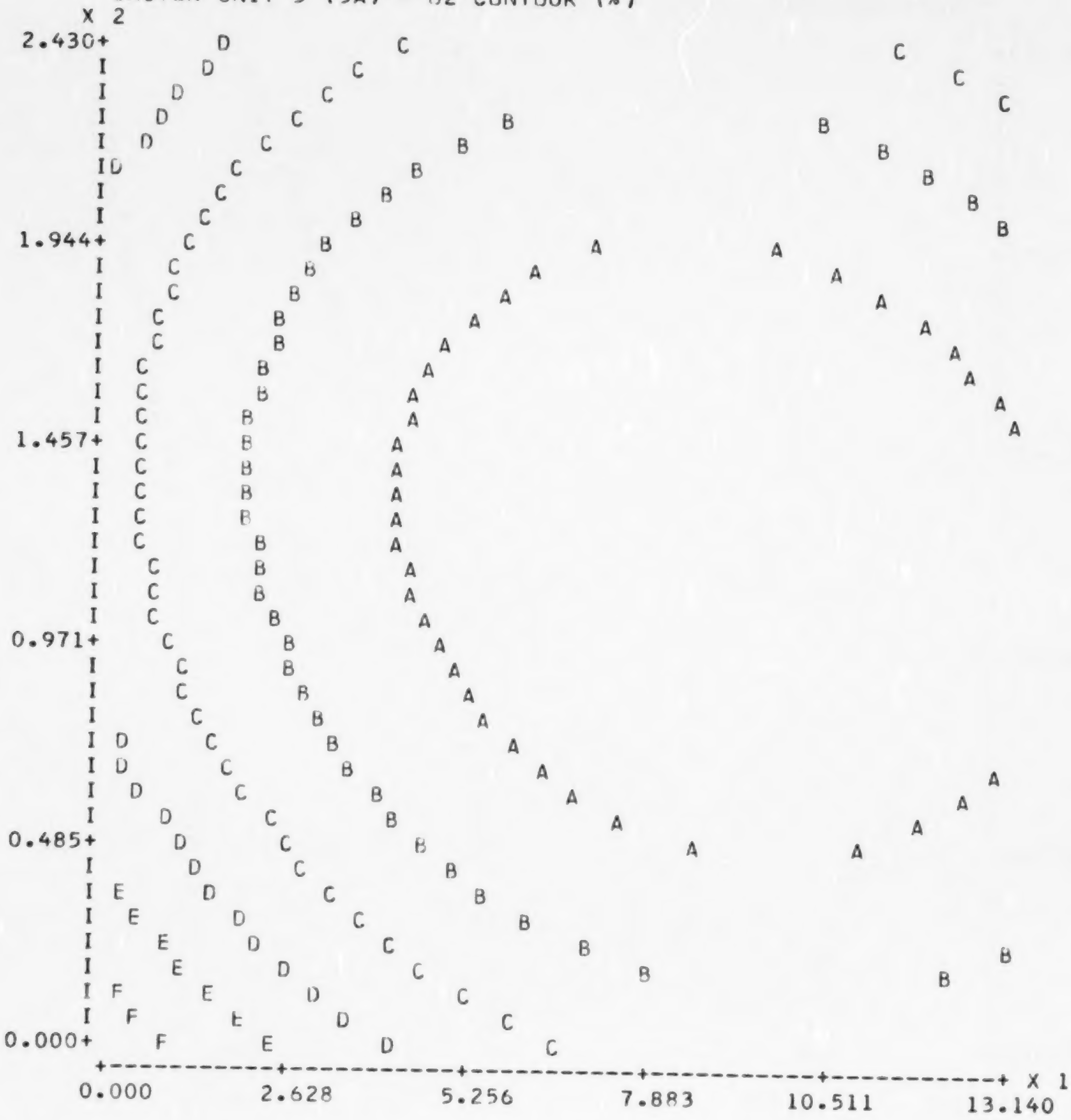
MORGANTOWN UNIT 1 (1B) - VELOCITY CONTOUR (M/S)



```
CODING OF                RESPONSE =
CONTOURS               0.17010E 02
A=  10.000            -0.11700E 01(X  1)
B=  15.000            -0.85000E 00(X  2)
C=  20.000             0.13000E 00(X  1)(X  1)
D=  25.000            -0.11400E 01(X  2)(X  2)
                       0.20000E 00(X  1)(X  2)
```

Figure 39

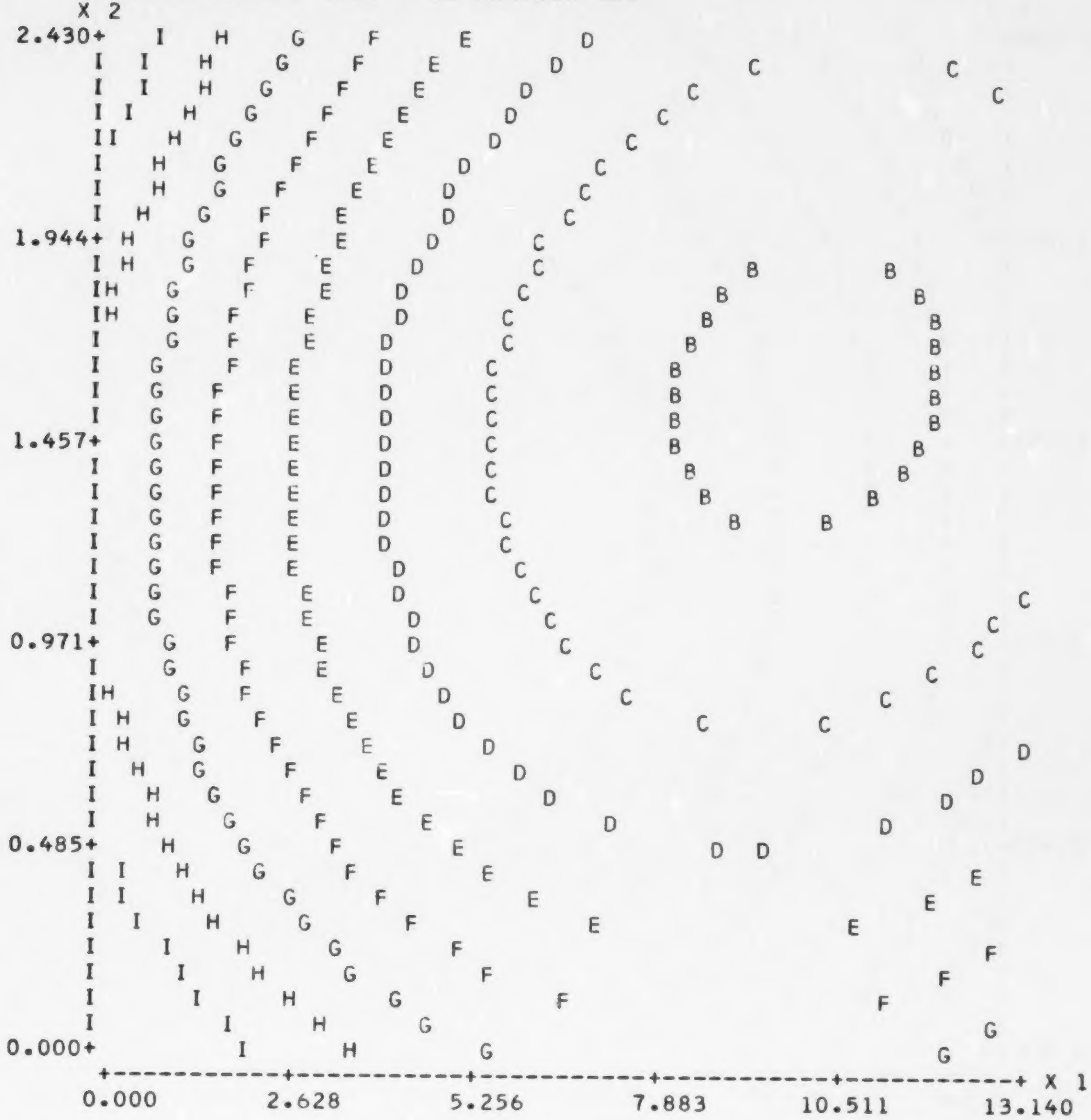
GASTON UNIT 5 (5A) - O2 CONTOUR (%)



```
CODING OF          RESPONSE =
CONTOURS          0.83400E 01
A=    5.500      -0.41000E 00(X  1)
B=    6.000      -0.23800E 01(X  2)
C=    6.500       0.20000E-01(X  1)(X  1)
D=    7.000       0.83000E 00(X  2)(X  2)
E=    7.500       0.40000E-01(X  1)(X  2)
F=    8.000
```

Figure 40

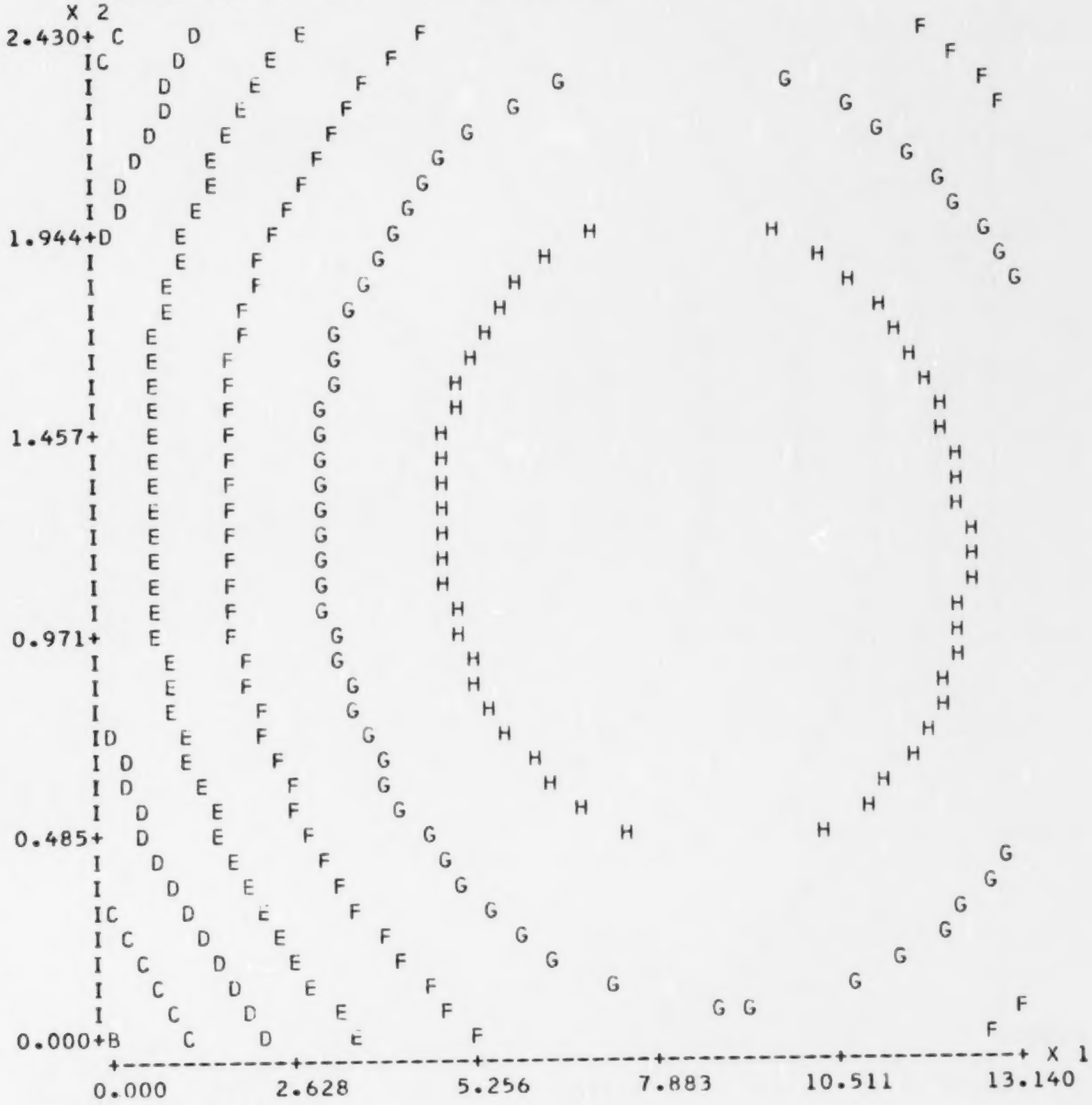
GASTON UNIT 5 (5B) - O2 CONTOUR (%)



```
CODING OF          RESPONSE =
CONTOURS          0.79300E 01
A=     3.000     -0.52000E 00(X  1)
B=     3.500     -0.24300E 01(X  2)
C=     4.000      0.30000E-01(X  1)(X  1)
D=     4.500      0.92000E 00(X  2)(X  2)
E=     5.000     -0.50000E-01(X  1)(X  2)
F=     5.500
G=     6.000
H=     6.500
I=     7.000
```

Figure 41

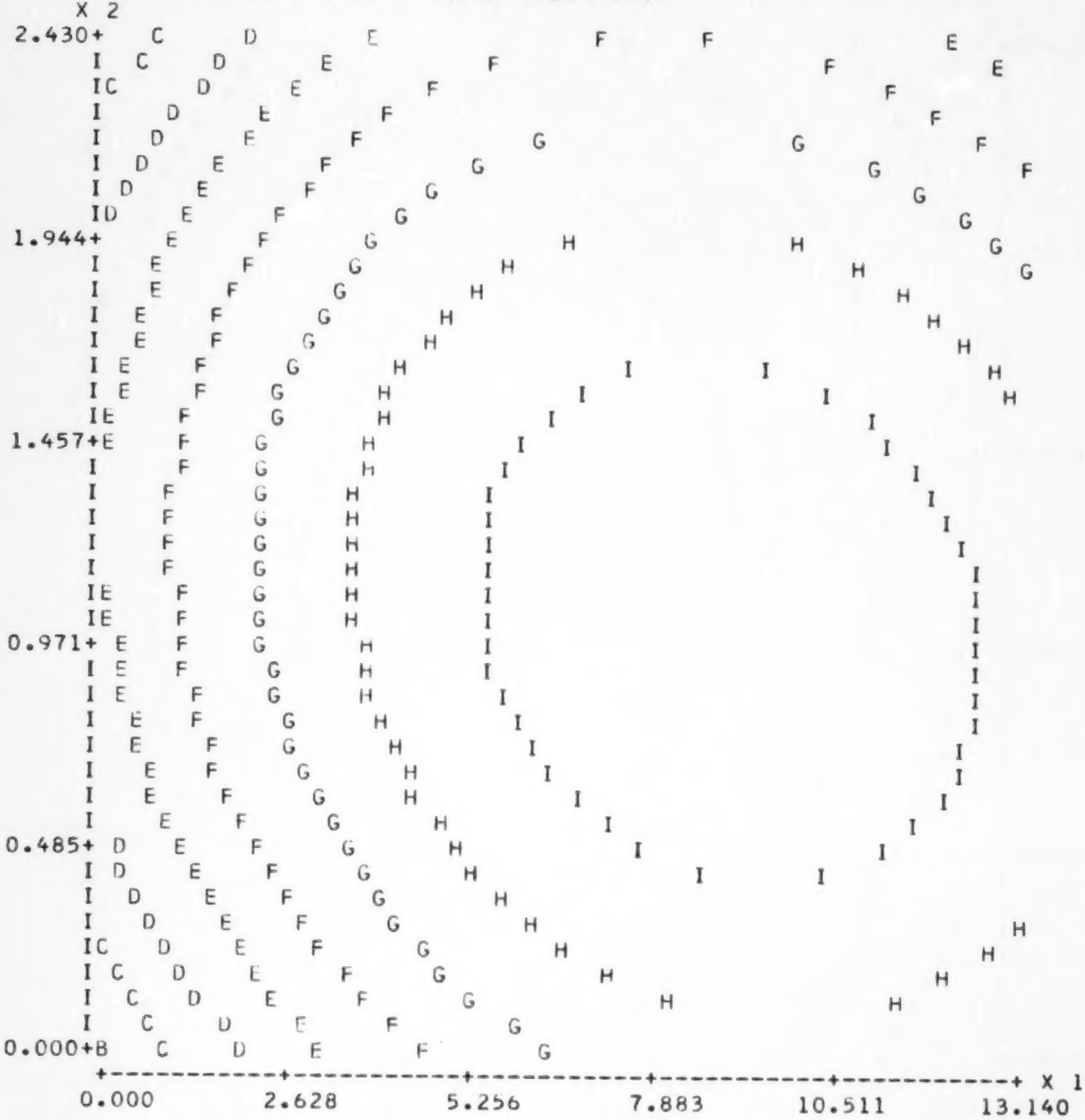
GASTON UNIT 5 (5A) - CO2 CONTOUR (%)



```
CODING OF           RESPONSE =
CONTOURS          0.94700E 01
A=    9.000       0.54000E 00(X  1)
B=    9.500       0.18900E 01(X  2)
C=   10.000      -0.30000E-01(X  1)(X  1)
D=   10.500      -0.71000E 00(X  2)(X  2)
E=   11.000      -0.20000E-01(X  1)(X  2)
F=   11.500
G=   12.000
H=   12.500
I=   13.000
```

Figure 42

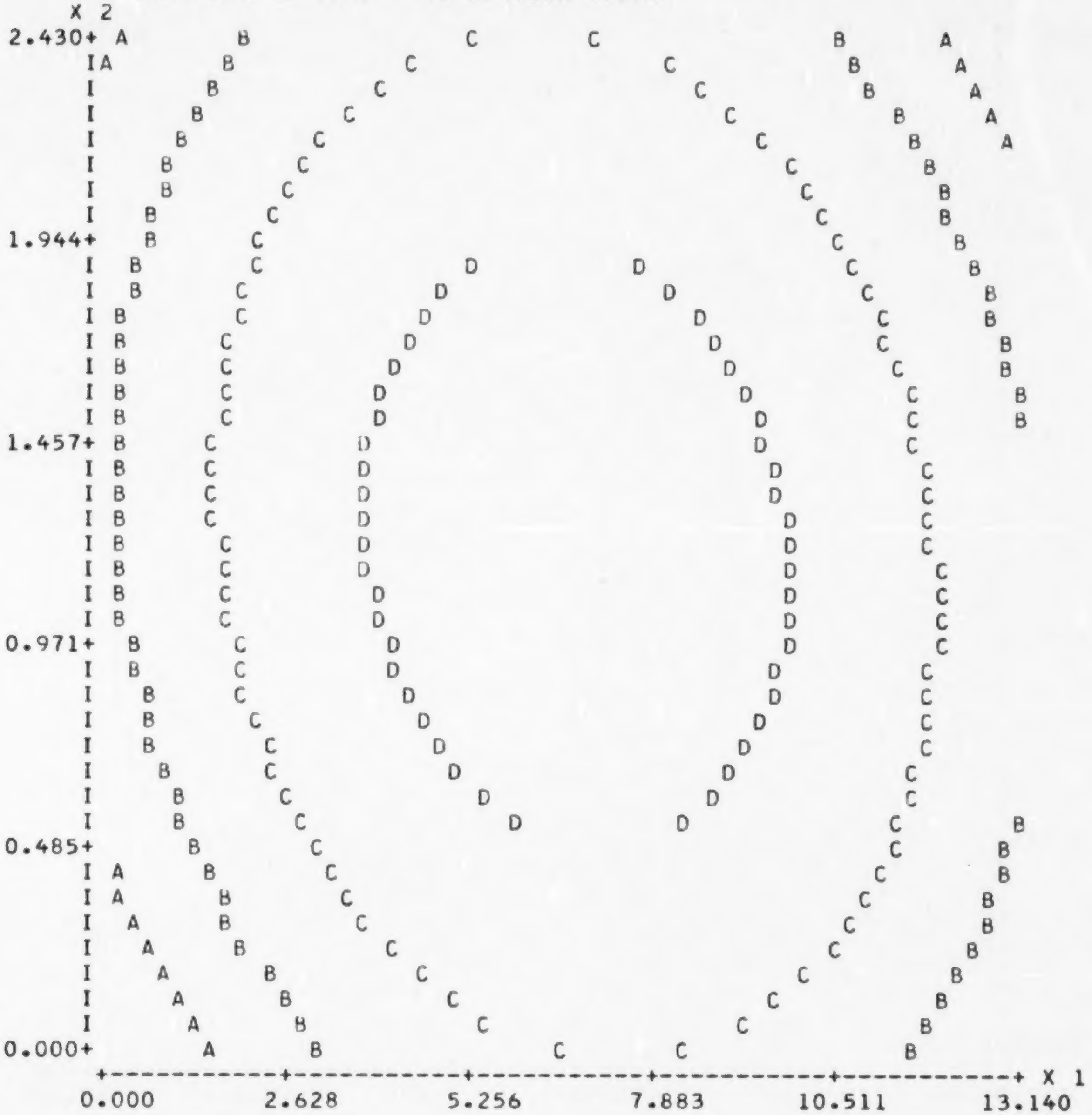
GASTON UNIT 5 (5B) - CO2 CONTOUR (%)



```
CODING OF            RESPONSE =
CONTOURS           0.99500E 01
A=    9.500        0.59000E 00(X  1)
B=   10.000        0.24800E 01(X  2)
C=   10.500       -0.30000E-01(X  1)(X  1)
D=   11.000       -0.98000E 00(X  2)(X  2)
E=   11.500       -0.50000E-01(X  1)(X  2)
F=   12.000
G=   12.500
H=   13.000
I=   13.500
J=   14.000
```

Figure 43

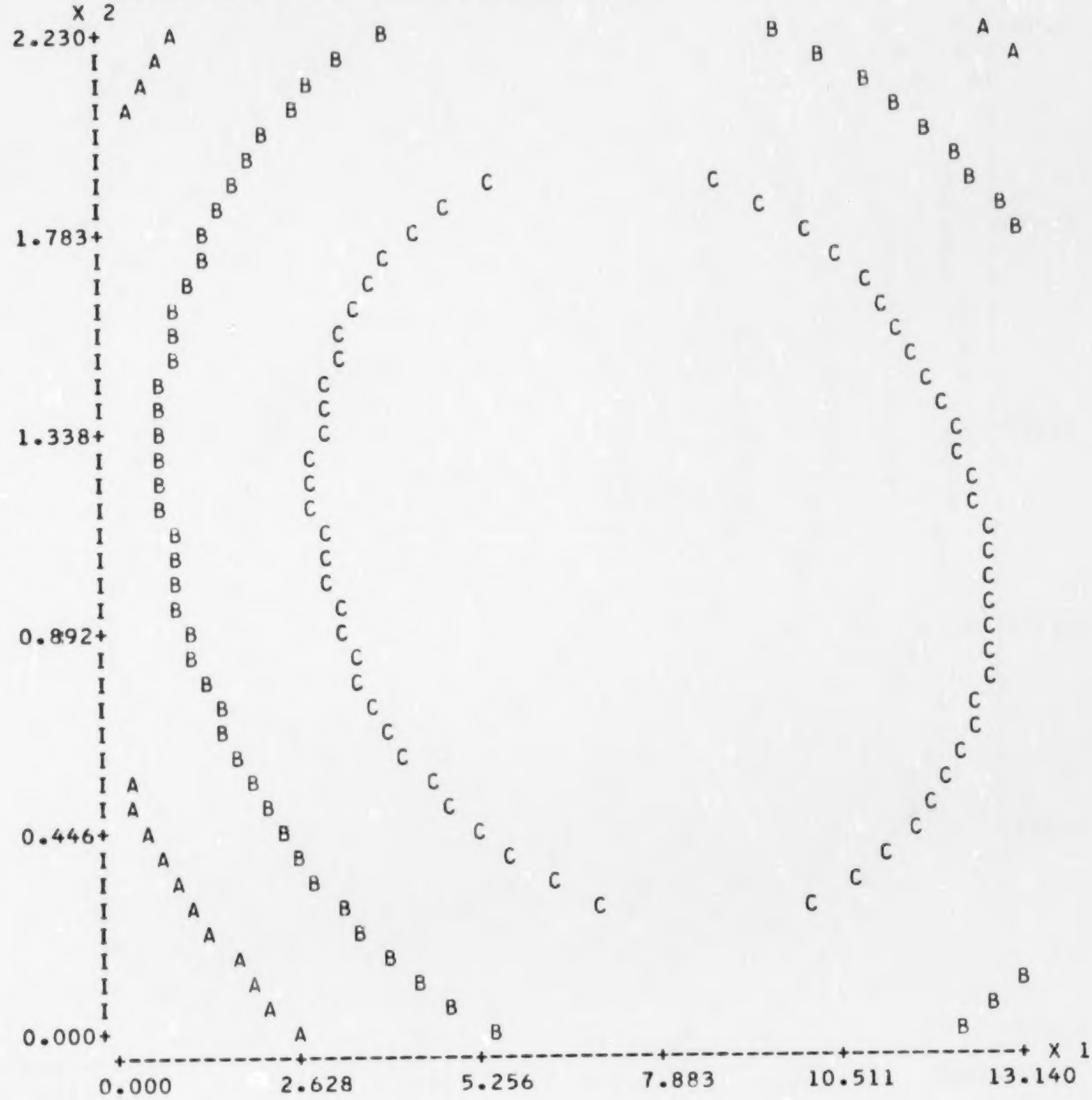
GASTON UNIT 5 (5A) - NO CONTOUR (PPM)



```
CODING OF          RESPONSE =
CONTOURS          0.42159E 03
A= 450.000        0.21460E 02(X  1)
B= 475.000        0.71950E 02(X  2)
C= 500.000       -0.14500E 01(X  1)(X  1)
D= 525.000       -0.25580E 02(X  2)(X  2)
E= 550.000       -0.14400E 01(X  1)(X  2)
```

Figure 44

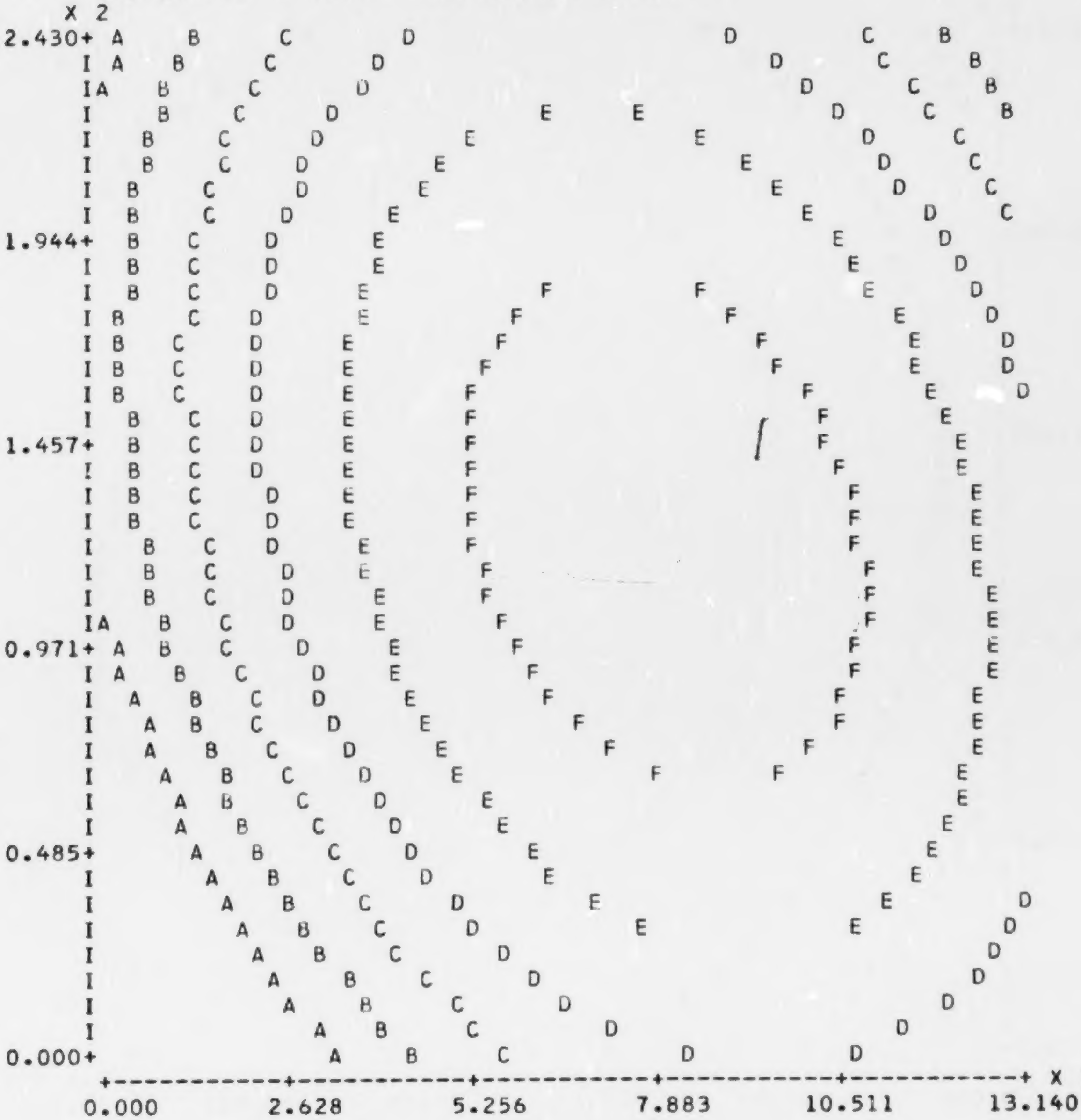
GASTON UNIT 5 (5B) - NO CONTOUR (PPM)



```
CODING OF              RESPONSE =
CONTOURS             0.36257E 03
A= 400.000           0.16730E 02(X  1)
B= 425.000           0.80730E 02(X  2)
C= 450.000          -0.95000E 00(X  1)(X  1)
D= 475.000          -0.30920E 02(X  2)(X  2)
E= 500.000          -0.16900E 01(X  1)(X  2)
```

Figure 45

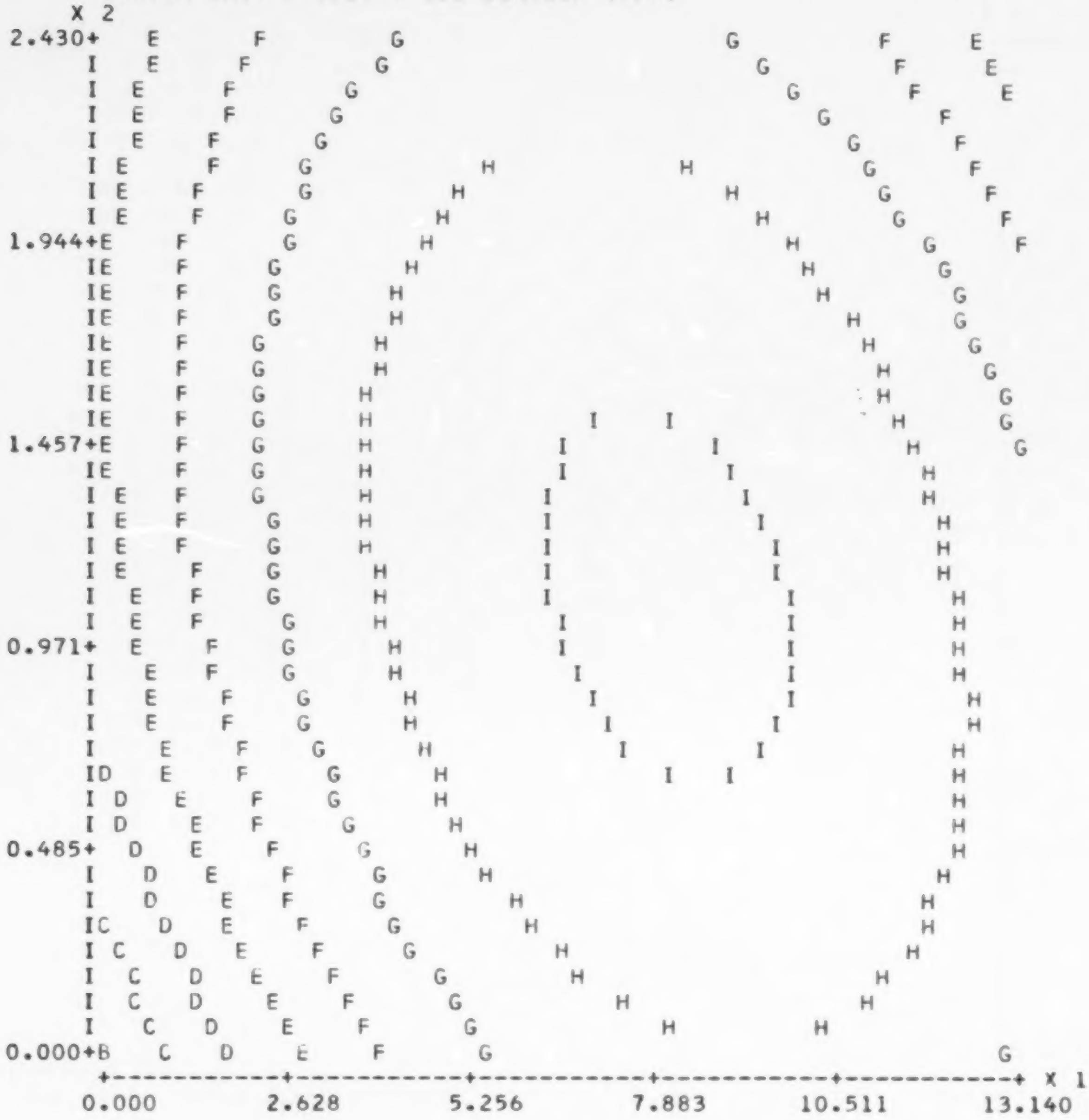
GASTON UNIT 5 (5A) - SO2 CONTOUR (PPM)



```
CODING OF          RESPONSE =
CONTOURS       0.58787E 03
A= 800.000      0.77700E 02(X  1)
B= 850.000      0.28772E 03(X  2)
C= 900.000     -0.41000E 01(X  1)(X  1)
D= 950.000     -0.84880E 02(X  2)(X  2)
E=1000.000     -0.93400E 01(X  1)(X  2)
F=1050.000
G=1100.000
```

Figure 46

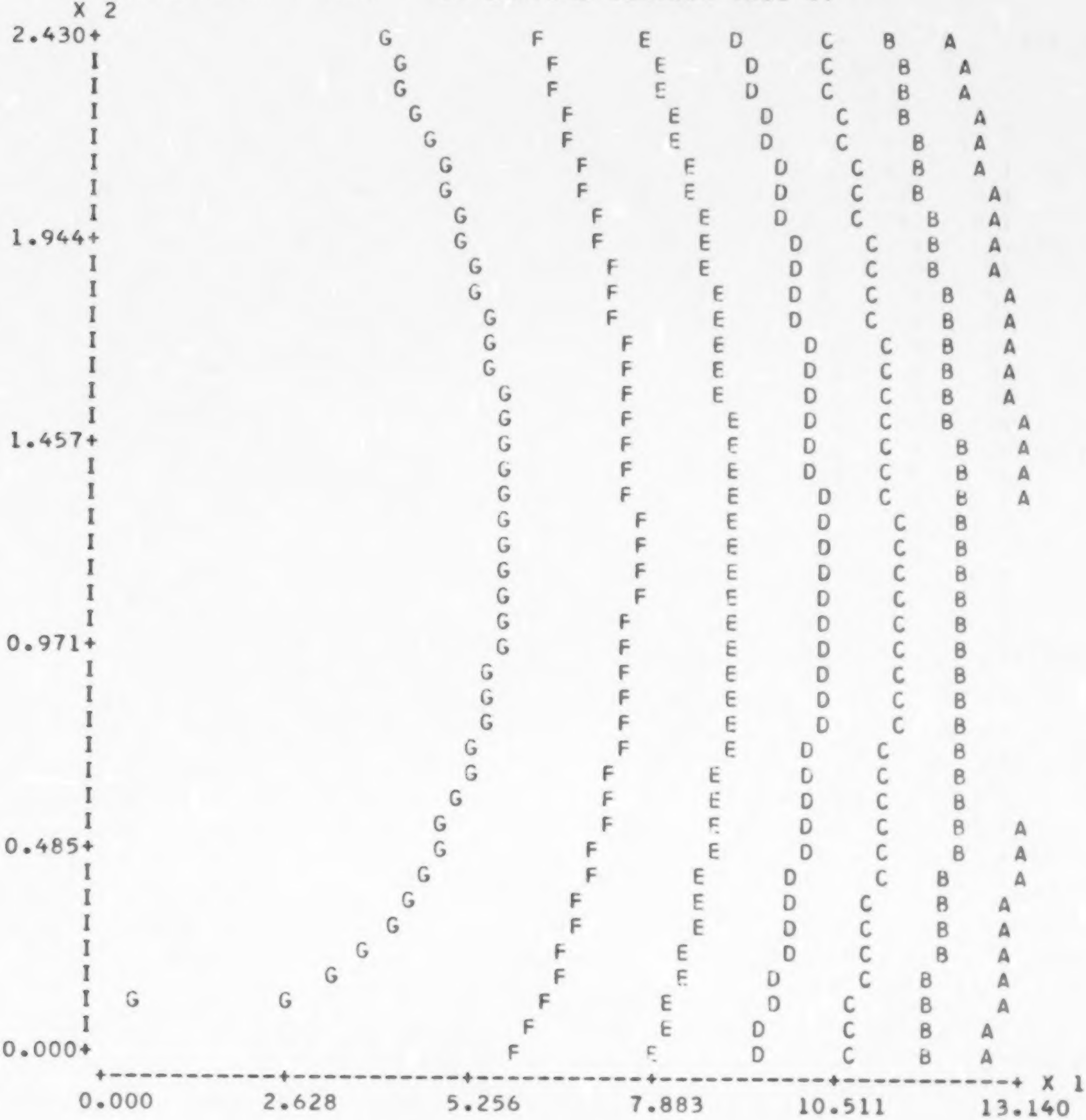
GASTON UNIT 5 (5B) - SO2 CONTOUR (PPM)



```
CODING OF                 RESPONSE =
CONTOURS                 0.74644E 03
A= 700.000               0.64980E 02(X  1)
B= 750.000               0.18422E 03(X  2)
C= 800.000              -0.35000E 01(X  1)(X  1)
D= 850.000              -0.55360E 02(X  2)(X  2)
E= 900.000              -0.77100E 01(X  1)(X  2)
F= 950.000
G=1000.000
H=1050.000
I=1100.000
J=1150.000
K=1200.000
```

Figure 47

GASTUN UNIT 5 (5A) - TEMPERATURE CONTOUR (DEG C)



```
CODING OF              RESPONSE =
CONTOURS             0.14868E 03
A= 120.000           0.80000E 00(X  1)
B= 125.000           0.85900E 01(X  2)
C= 130.000          -0.24000E 00(X  1)(X  1)
D= 135.000          -0.28500E 01(X  2)(X  2)
E= 140.000          -0.24000E 00(X  1)(X  2)
F= 145.000
G= 150.000
```

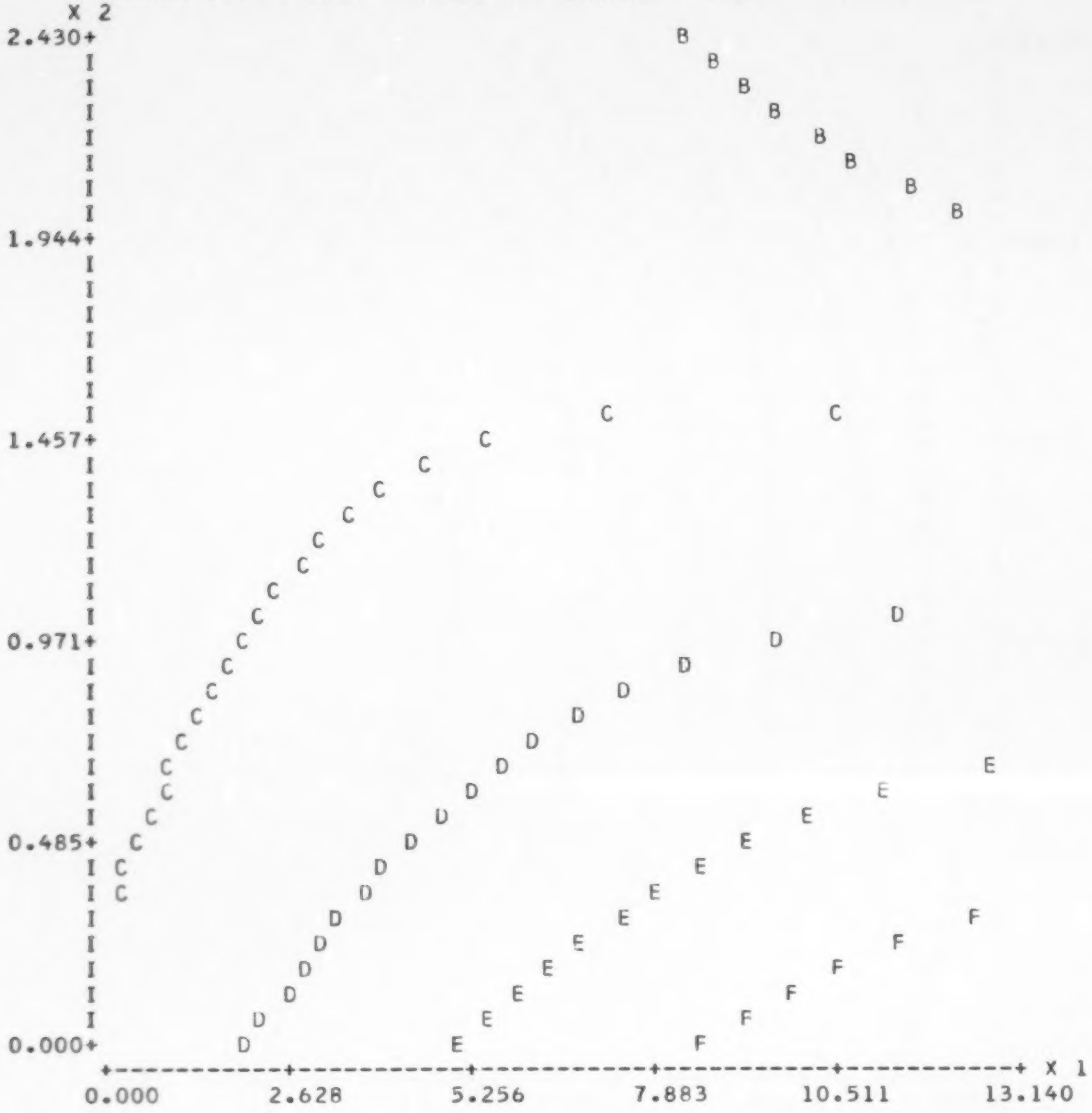
Figure 48

```
         GASTON UNIT 5 (5B) - TEMPERATURE CONTOUR (DEG C)
      X 2
   2.430+      A    B    C      D       E          F
        I     A    B    C      D      E          F
        I    A    B     C     D      E         F
        I    A    B    C     D      E         F
        I   A    B    C     D      E        F                 G
        I   A   B     C    D      E        F              G
        I  A    B    C     D     E        F            G
        I  A   B    C     D      E       F           G
   1.944+ A    B    C     D     E       F           G
        I A    B    C    D     E       F          G
        I A   B    C     D     E       F         G
        IA    B    C    D     E       F         G
        IA    B    C    D     E      F         G
        I    B    C     D     E      F         G
        I    B    C    D     E       F        G
        I    B    C    D     E      F        G
   1.457+    B    C    D     E      F        G                   H
        I    B   C     D     E      F        G                 H
        I    B   C     D     E      F        G                H
        I    B   C     D    E      F        G                H
        I    B   C     D    E      F        G               H
        I    B   C     D    E      F        G               H
        I    B   C     D    E      F        G                H
        I    B    C    D     E      F       G                H
   0.971+    B    C    D     E      F        G                H
        I    B    C    D     E      F        G                 H
        I    B    C    D     E      F        G                   H
        IA   B    C    D     E       F        G
        IA    B    C    D     E      F        G
        I A   B    C    D     E      F         G
        I A   B    C     D     E      F         G
        I A    B    C    D     E       F         G
   0.485+  A   B    C    D      E      F          G
        I  A    B   C     D     E       F          G
        I  A    B    C     D     E       F          G
        I   A   B     C    D      E       F           G
        I   A    B    C     D      E       F            G
        I    A    B    C     D     E        F              G
        I     A   B    C     D      E        F                 G
        I     A    B    C     D      E         F
   0.000+      A    B    C     D       E        F
         +-----------+-----------+-----------+-----------+-----------+ X 1
        0.000       2.628       5.256       7.883      10.511      13.140


                      CODING OF           RESPONSE =
                      CONTOURS         0.93400E 02
                      A= 100.000       0.54700E 01(X  1)
                      B= 105.000       0.12130E 02(X  2)
                      C= 110.000      -0.21000E 00(X  1)(X  1)
                      D= 115.000      -0.49400E 01(X  2)(X  2)
                      E= 120.000      -0.60000E-01(X  1)(X  2)
                      F= 125.000
                      G= 130.000
                      H= 135.000
```

Figure 49

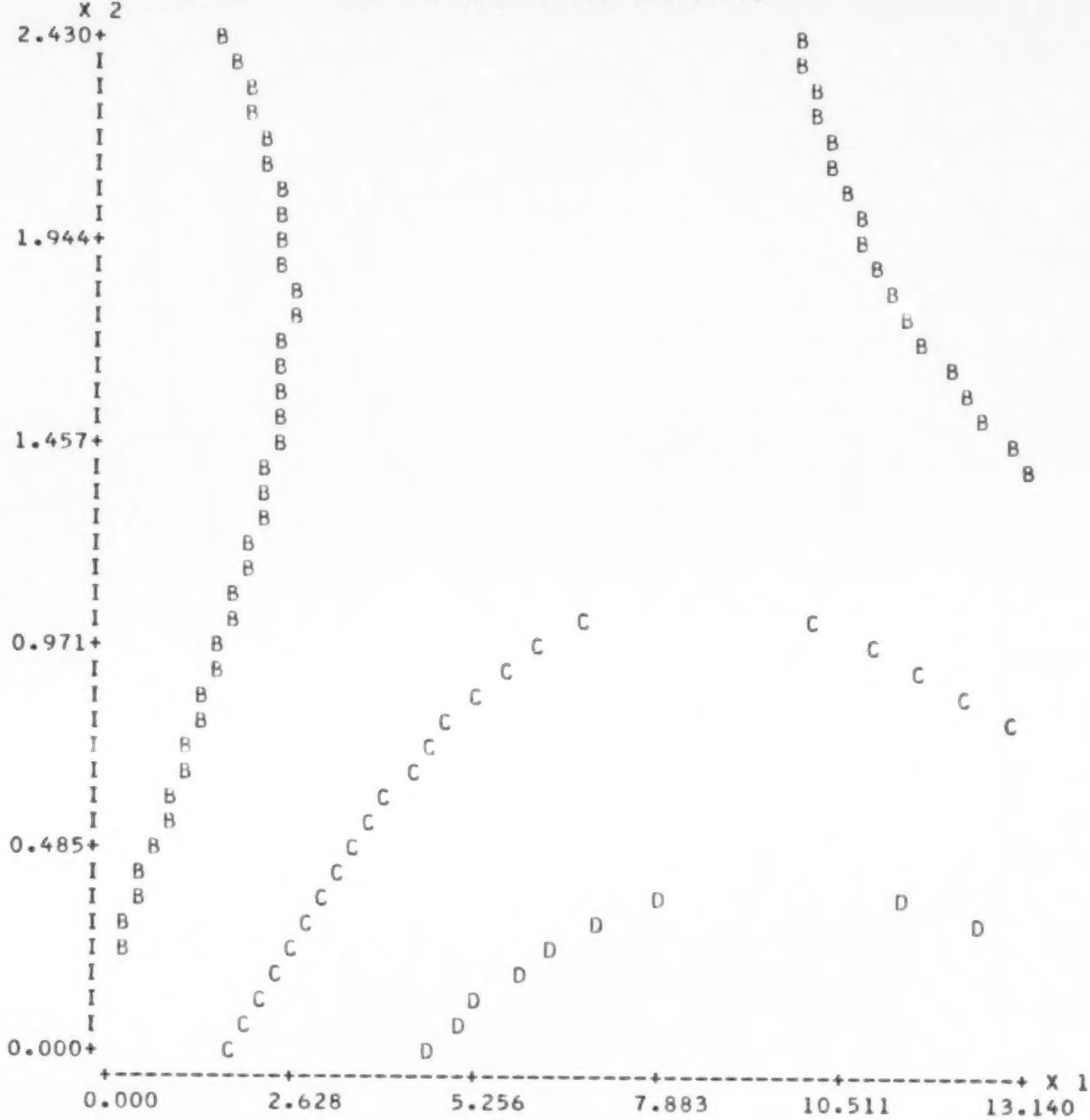
GASTON UNIT 5 (5A) - VELOCITY CONTOUR (M/S)



```
CODING OF           RESPONSE =
CONTOURS          0.16370E 02
A=    5.000       0.18400E 01(X  1)
B=   10.000      -0.49300E 01(X  2)
C=   15.000      -0.30000E-01(X  1)(X  1)
D=   20.000       0.16600E 01(X  2)(X  2)
E=   25.000      -0.86000E 00(X  1)(X  2)
F=   30.000
```

Figure 50

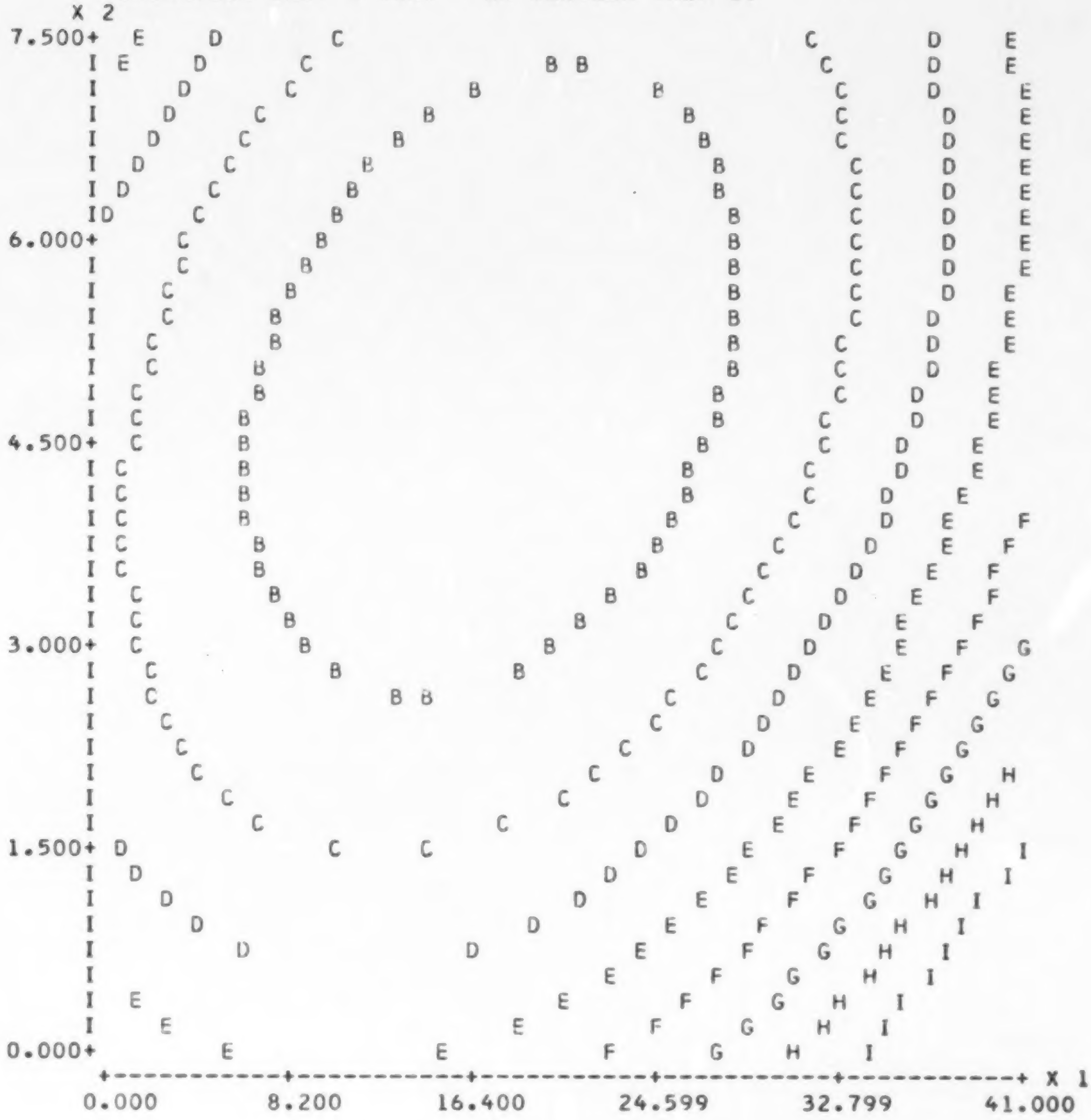
GASTON UNIT 5 (5B) - VELOCITY CONTOUR (M/S)



```
CODING OF               RESPONSE =
CONTOURS               0.11140E 02
A=    5.000             0.24900E 01(X  1)
B=   10.000            -0.63200E 01(X  2)
C=   15.000            -0.12000E 00(X  1)(X  1)
D=   20.000             0.21000E 01(X  2)(X  2)
E=   25.000            -0.46000E 00(X  1)(X  2)
F=   30.000
```

Figure 51

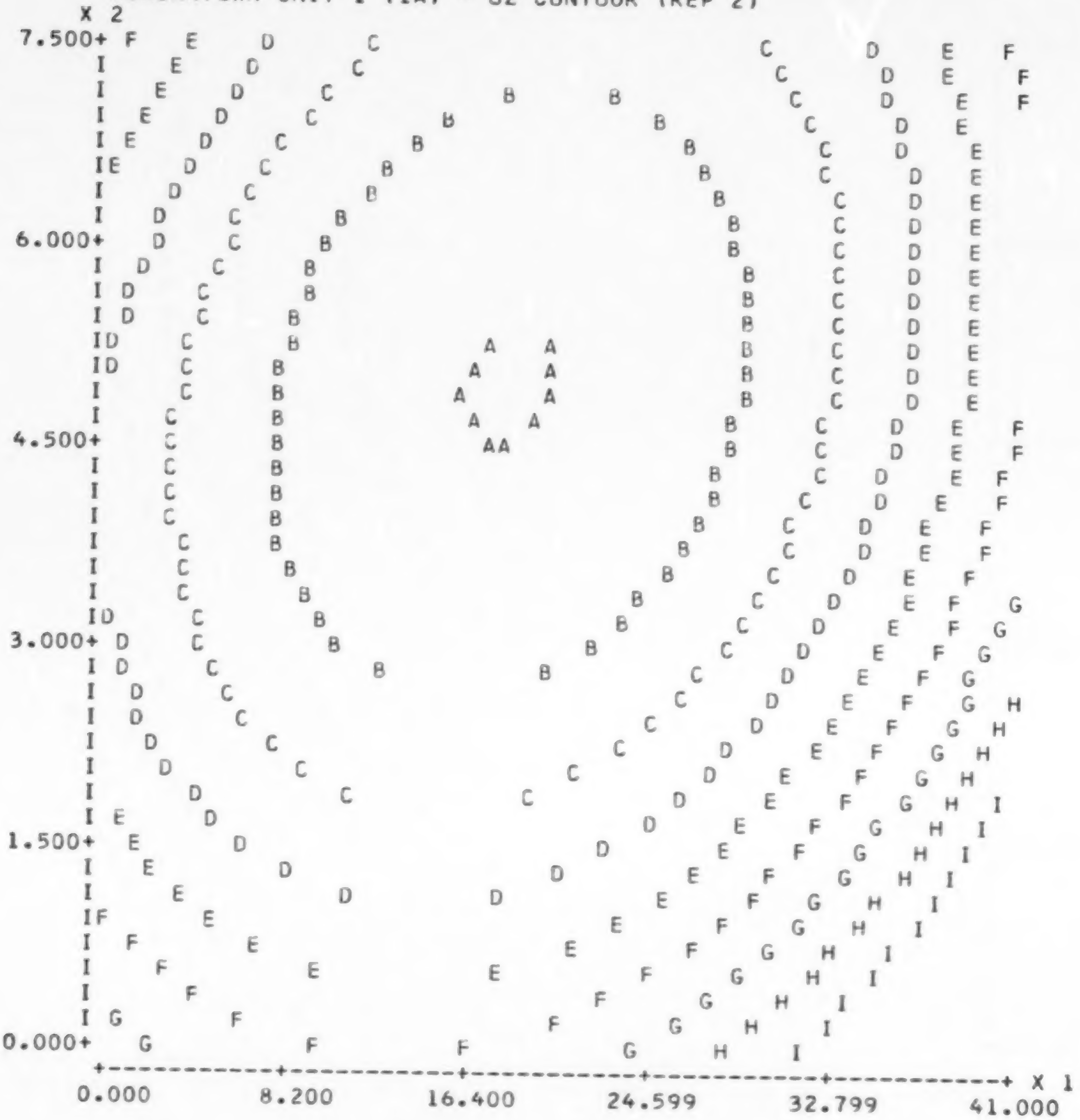
MORGANTOWN UNIT 1 (1A) - O2 CONTOUR (REP 1)



```
CODING OF            RESPONSE =
CONTOURS            0.63028E 01
A=    4.000        -0.76011E-01(X  1)
B=    4.500        -0.62655E 00(X  2)
C=    5.000         0.37289E-02(X  1)(X  1)
D=    5.500         0.81249E-01(X  2)(X  2)
E=    6.000        -0.10512E-01(X  1)(X  2)
F=    6.500
G=    7.000
H=    7.500
I=    8.000
```

Figure 52

MORGANTOWN UNIT 1 (1A) - O2 CONTOUR (REP 2)

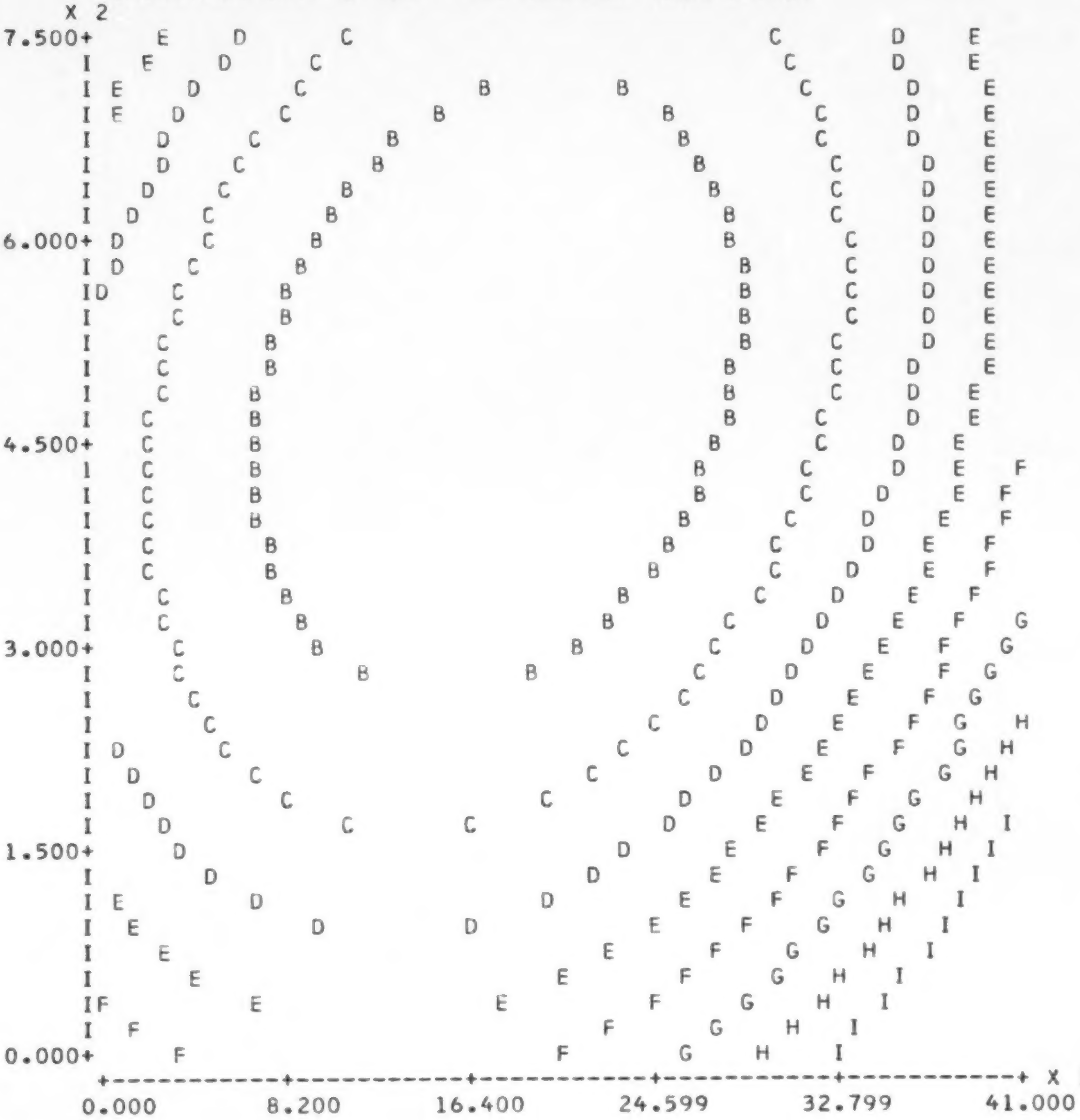


CODING OF
CONTOURS
A= 4.000
B= 4.500
C= 5.000
D= 5.500
E= 6.000
F= 6.500
G= 7.000
H= 7.500
I= 8.000

RESPONSE =
0.72420E 01
-0.12192E 00(X 1)
-0.87892E 00(X 2)
0.46751E-02(X 1)(X 1)
0.10625E 00(X 2)(X 2)
-0.93550E-02(X 1)(X 2)

Figure 53

MORGANTOWN UNIT 1 (1A) - O2 CONTOUR (COMPOSITE)



```
CODING OF              RESPONSE =
CONTOURS             0.67724E 01
A=    4.000         -0.98969E-01(X  1)
B=    4.500         -0.75274E 00(X  2)
C=    5.000          0.42020E-02(X  1)(X  1)
D=    5.500          0.93749E-01(X  2)(X  2)
E=    6.000         -0.99336E-02(X  1)(X  2)
F=    6.500
G=    7.000
H=    7.500
I=    8.000
```

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ACKNOWLEDGMENTS

The authors wish to acknowledge the constructive participation of Dr. H. M. Barnes, EPA Project Officer, in planning the field test program. The helpful cooperation of two of the major U.S. utility boiler manufacturers, Combustion Engineering and Babcock and Wilcox, were essential to selecting representative boilers for the field test program. The voluntary participation of electric utility boiler companies in making their boilers available is gratefully acknowledged. These utility companies included the Tennessee Valley Authority, Southern Electric Generating Company, Alabama Power Company, Potomac Electric Power Company, and the Salt River Project. The invaluable assistance of Messrs. L. W. Blanken, R. W. Schroeder, R. J. Johnston, W. Petuchevas, V. S. Engleman, H. T. Oakley, R. P. Smith and Mrs. M. V. Thompson in these field studies is also acknowledged.